Confronting Science Misconceptions with the Help of a Computer

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Abstract

A long standing aim of science educators is to help secondary school science students to learn efficiently through various exploratory regimes. A further aim, currently held by several leading science educators, is to promote learning by confronting students with the inconsistencies entailed by their own beliefs. The claim at the heart of the thesis is that well designed computer-based modelling facilities can provide advantages over many approaches exploiting other media and that such facilities can be used to promote the kinds of conflict that are believed to be beneficial.

This claim is explored through an analysis of the rôle of modelling in science, the nature of student's beliefs about physical phenomena that conflict with more established beliefs and of how computer-based modelling environments can promote learning through modelling. This requires consideration of a wide number of issues relating to educational theory and practice, student learning, the design of modelling environments and methodologies and techniques taken from the field of Artificial Intelligence.

The methodology adopted required that a number of computer environments be constructed and observations made of their usage by students. The environments are used to focus attention on the various issues.

The results contained within this thesis include a short analysis of the educational implications if the use of modelling environments were to be more widely adopted, an analysis of the strengths and weaknesses of these systems in terms of how they promote student learning —particularly in relation to the nature of the beliefs that students hold— and design criteria for how future systems might be built.

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Introduction

> *...for her own mother lived the latter years of her life in the horrible suspicion that electricity was dripping invisibly all over the house. It leaked, she contended, out of empty sockets if the wall switch had been left on. She would go around screwing in bulbs, and if they lighted up she would hastily and fearfully turn off the wall switch and go back to her* Pearson's *or* Everybody's, *happy in the satisfaction that she had stopped not only a costly but a dangerous leakage. Nothing could ever clear this up for her.*
> *—James Thurber, The Car We Had to Push, The Thurber Carnival, 1962.*

The fundamental concern of this thesis is to design computer systems to help secondary school students assess the implications of their beliefs about the physical world.

The approach taken is inspired by work done within the field of Artificial Intelligence (AI). What follows is a description of an approach which is driven by two major concerns: that both the known problems in teaching a particular domain and the known difficulties that students have with learning in that domain must be respected. These two issues are distinct but mutually dependent.

The particular domain chosen is a subset of the natural sciences. This is further restricted to physics for practical reasons. Later on, the reasons for the selection of specific subsections of physics are given.

The type of learning environment adopted falls into the modelling category. The next section features a short discussion about the nature of this modelling framework.

In order to pursue the general goals of this research it is necessary to explore:

- Provision of simple modelling languages
- Importance of students' misconceptions
- Educational issues re: management, systems and physics learning

The rest of the chapter will feature discussions on the main concerns of the thesis:

- The advantages and disadvantages of modelling
- Current work in providing modelling environments
- Research into students' science misconceptions

This is followed by an overview of the thesis.

1.1 What Kind of Learning Environment?

The "Learning Mathematics through Programming" project at the Department of Artificial Intelligence at Edinburgh University was based on the idea of students constructing a representation of their mathematical knowledge using LOGO [Howe & du Boulay 79, Howe et al 82]. The idea of extending this work to the science domain was one motivating factor in choosing a modelling approach.

A modelling environment may be embedded in a larger system which constrains the activities of the student in some way. Such a system can be seen as an example of an *Intelligent Teaching System* (ITS).

It is often stated that there are two distinct schools of thought in the Artificial Intelligence community about the nature of AI work in the education field. On the one hand are those who can be loosely labelled the *Discovery Learning* group and on the other hand we have the ITS group. The former believe that the rôle of AI is to provide carefully tailored tools which will encourage students to structure their own understanding. The management of the learning process lies with the student, the teacher or some cooperation between them. The latter group believes that there has to be a manager for the learning process which is resident in the computational system. This system may, for a given domain, set up a syllabus, maintain some records about the student and provide tutorial feedback.

It is believed that certain extreme positions taken by members of these two groups are flawed. Further, there is a need to find ways in which the advantages of both approaches may be taken into account.

The Discovery Learning approach is badly flawed if the assumption is that the whole environment in which learning is supposed to take place is the student and the computational environment. It is certain that most students need a variety of forms of assistance in such situations. The remedy has often been seen as residing in the rôle of classroom teachers but they are not usually free to monitor the work of the student in an efficient way.

ITS system designers have tried to set up architectures that address the various hard problems that relate to automating the activities of an intelligent teacher. The problem here is that, if we accept the standard framework for Intelligent Computer Assisted Instruction (ICAI), then we need knowledge of the domain, a model of the student, knowledge of the various teaching skills and a manager for the learning process which utilises these sources of knowledge while conducting a dialogue with the student. If we apply the dictum that the easiest research tasks are those that are tackled first then it comes as no great surprise that most work in AI has concentrated on representing the domain and least on management of the learning process. There is also a need for more work to be done in the realm of modelling both students and the necessary teaching skills.

To produce systems that are usable in normal classrooms there are two fundamental options: we could start from some ideal architecture for an ITS and simplify until we have a system that is realisable or we can start from a simple discovery learning position and see how to strengthen it with further computational forms of aid.

The simple modelling environment can be strengthened by the provision of a set of integrated tools which are under the control of the student. The nature of the tools that might prove useful is of interest but depends to a great degree on an analysis of the needs of the students.

1.2 Why Model?

There are some good reasons why it is desirable for physics students to engage in modelling activities. On the other hand, there are some dangers which have to be taken into account. We shall briefly consider:

- Models in Science
- Models as an Activity
- Modelling and Learning
- Modelling as a Substitute for Experimentation
- The Inevitable Risks

First we will look at the place of models in the domain of science.

1.2.1 Models in Science

It is the intention to produce a computer environment which allows students to model a variety of physical situations. With what kinds of model will these students be concerned, how do scientists themselves use models and how do educationalists believe models are —or should be— used?

The classification upon which the following discussion is based is a shallow one but captures most of the issues that are of interest.

Formal Models

This kind of model is sometimes considered to be an instantiation of a theory. In some sense, a formal model is a theory. The history of the philosophy of science illustrates a number of attempts to formalise exactly what is meant by a scientific theory. For a fair part of this century the standard (or 'received') view has been based on the work of logical positivists and their descendants. This formalisation has included a set of theoretical terms, a set of observables and a set of coordinating definitions that are intended to impart meaning to the theoretical terms. An example taken from the domain of measurement might include the theoretical term *length* and the observable *standard metre*. We then need a coordinating definition that provides a means of relating the length of an object to the standard metre.

A major problem is that it is extremely difficult to use this formalisation to capture, for example, Newton's (own) theory of gravitation as a computer program. Philosophers still argue about many of the details of the original theory[1]. The issue here is how to provide the necessary semantics in an explicit way. So, if we wish to represent Newton's theory of gravitation —including the

[1]For example, Putnam has argued that even the standard version of this theory needs to be supplemented before it can be used to make any predictions —see the discussion by Putnam in [Suppe 77].

necessary semantics— as a computer program then we have a problem. If we wish students to model this theory we have an even bigger problem.

One educational consequence of these difficulties is that we are tempted to provide all the necessary substructure for a formal model and focus on one key equation. We then rip this equation out and ask the student to replace it with a variety of plausible alternatives. If the equation is parameterised, then the student may be asked to experiment with varying these parameters. Occasionally, the student is asked to experiment with a class of functions. This view of modelling is unfortunate. Davies, for example, states that a (mathematical) model consists of sets of equations *together* with the circumstances under which the equations are applicable. He also points out that even these preconditions are often neglected [Davies 78]. In the attempt to formalise reasoning about connected particles at the level of an English 'A' Level student, Bundy has also noted the large amount of implicit knowledge needed which is rarely touched upon in the standard classroom teaching of statics and dynamics [Bundy et al 79].

A further problem with formal modelling: making a theory completely explicit may mean spending little effort on understanding how theories change[2]. Further, if the student is only required to successfully parameterise some equation to complete a model then how is s/he to spot the inadequacies of the model? We would like to engage in modelling that helps students to go through a succession of qualitatively different models in a way that leads to a better appreciation of the provisional nature of models.

Analogue Models

The other distinct type of model considered here is analogue. This type of model has to be structurally similar to the thing modelled[3].

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[2]Putnam essentially raises this point in [Suppe 77].

[3]Black further distinguishes between scale (or iconic) and analogue models [Black 62]. The terms *iconic* and *analogue* will be taken as synonymous throughout this thesis.

In the context of analogue models, Hesse has made the observation that any analogy can be regarded as composed of three parts [Hesse 66]. These are the positive analogy, the negative analogy and the neutral analogy. The positive analogy is that part of the analogy which is known to be correct while the negative part is known to be incorrect. The neutral analogy consists of features of the model that cannot yet be identified as either parts of the positive or negative analogies.

In general, the modelling that is explored in this thesis is to be interpreted as analogue rather than formal modelling.

The Uses of Models

Explanation and Prediction The main functions usually ascribed to models are those of explanation and prediction [Gilbert & Osborne 80] although some doubt exists as to whether one can successfully discriminate between these two functions [Suppe 77, Hempel 65]. Hanson, however, disagrees [Hanson 71]. Gee goes even further in saying that models do not explain anything [Gee 78] —but what is an explanation? One view is that it is simply a logical inference relative to some knowledge base with the thing to be explained as the conclusion. In the school environment we see another meaning that can be attached to the word 'explanation' such that an explanation of some event may well include analogical references and some means of mapping events in the analogue world to events in the world that is to be explained.

We do not assume that the ability to provide an analogical explanation necessarily means that the explanation must be 'correct'. Here, we are more interested in the rôle of analogy in both the generation and acceptability of an explanation. Thus if Gee means that explanations of the behaviour of the analogue model do not of themselves constitute an explanation of the behaviour of the thing modelled then he is correct but an explanation of some feature of the analogue model can still be transferred to the thing modelled by means of the analogy itself. If this cannot be done then the value of the analogue model is in great doubt.

Perhaps Harré makes the distinction between explanation and prediction clearer by describing the functions of analogue models as logical and epistemological [Harré 72]. Logical deduction based on the model are the predictions, and explanations are based on the epistemological function.

The Heuristic Uses of Models Other virtues are associated with the uses of models. Certainly, there is a heuristic value (see [Chalmers 75] for an example). Hesse sees novel ideas growing from attempts to use the neutral analogy as sources of predictions [Hesse 66] while Gee feels that a model enables the user to "see the forest for the trees" [Gee 78]. In a more informal vein, Gilbert and Osborne note that models being a caricature of reality are used to polarise one's thinking by throwing certain features into sharp relief [Gilbert & Osborne 80]. It has also been observed that students often learn new concepts via analogue models. Nagel outlines this usage as a means of quickly describing the rules of correspondence between theoretical terms and observables [Nagel 61]. Bullock sees models as having a psychological rôle [Bullock 79] in the classroom and Ormerod sees models as providing the opportunity to present ideas in a simplified way and also to present a consistent explanation of physical phenomena [Ormerod 78].

Scientists, Students and the Uses of Models One of the goals of science education is to get our students to think and behave like 'scientists'. Notwithstanding the difficulty of defining exactly what a scientist thinks and does, scientists both build and use models. We need some picture of "the Model Builder as Mature Scientist".

Contrasting the student's model building with that of a practicing scientist, Gilbert and Osborne note that the scientist builds up a mental 'model' through continued experimentation and through previous experience, knowledge of theory and the imaginative use of analogy [Gilbert & Osborne 80].

This is not so obviously the case for school students as they are likely to have little chance for continued experiment, little ability to transfer learning from one area to another, limited background knowledge and they are extremely unlikely to make a constructive use of analogy. They can be expected, however, to use analogy in an imaginative way [Driver & Easley 78, Driver 81].

Teachers, Students and the Uses of Models We will be looking at models that are built using a computer system. In this situation, the system may be programmed by the student to provide an informal interpretation of a theoretical model. Thus the student explores the consequences of a model which is, in principle, capable of being made completely explicit. This approach is more in tune with the Popperian approach to science in that the model can be regarded as a hypothesis to be explored by the student who can then compare it with what really happens. Thus one can maintain that the criticism that a computer model of some aspect of the real world is always less useful than observations in the real world assumes an approach to science which is based on the belief of there being some absolute truths that can be discovered. There are some practical problems to be overcome if the modelling approach is to become more acceptable in the classroom —not least of which is the apparent reluctance of science teachers to incorporate the hypothetico-deductive approach into their classroom teaching [Cawthorn & Rowell 78].

Far too often, experiments are presented to students as demonstration of well known truths or as attempts to convince the student on some psychological level. One can go further and claim that models presented in the physics classroom are frequently subject to the same criticisms. One long term goal is to help to make it easier for science teachers to adopt a modelling approach to physics by providing better computer tools for modelling.

At the worst, the systems described herein were used by students to deduce facts against a backdrop of certain assumptions. At best, the systems described later should permit the more able student to seek disparities between the explicit models presented and the corresponding 'real world' behaviour —this is a far more Popperian approach altogether.

1.2.2 Modelling as an Activity

We need to unpick the various phases in modelling. The defining of objects — data structures, the defining of relationships between objects and the defining of actions upon the objects by the objects —the procedures. In practice, these three activities do not necessarily occur in the order given above —although this order fits a fairly standard prescription. We also need an interpreter which can run the model —this implies that procedures will have (explicit or implicit) conditions which determine whether they will be activated.

Before exploring the three basic activities in more detail we first define more carefully the constitution of a model. We will divide a model into three categories:

- Objects
- Relationships between Objects
- Actions upon Objects

After this, we will look at three kinds of modelling activity:

- Modelling a System
- Modelling Relationships
- Modelling Objects

Objects

We need some objects for our model which will need to be instances chosen from a set of object classes. For the moment, let us shelve the question as to whether the objects can be abstract and consider one example chosen from the area of electrical circuits. We may wish to construct a circuit using a battery, a resistor and two wires. The battery we choose will be an instance chosen from among the range of possible batteries. This range of possibilities is the *battery* class. Embedded in the representation chosen for the *battery* class will be a number of pieces of information such as, in the case of the battery, that every battery has an associated electromotive force.

Thus any electrical circuit specification involves a number of instances of objects selected from the set of all the appropriate object classes that are available to the modeller.

Every object class must be associated with a set of *property classes.* In the case of the battery above, these classes might be the *EMF* class and the *internal resistance* class. We may think of the modeller being provided with (or defining) a set of property classes. The modeller can use this set to choose a subset of property classes that may be related with a given object class. When an instance of an object is chosen it will also be necessary to choose an instance corresponding to each property class associated with the relevant object class.

Relationships between Objects

We will not only need to choose instances of objects we will also need to have a method of relating objects to one another through relationships that hold between various property classes and between instances of property classes. We will need a set of relationship classes from which to select. Each relationship class will need to be defined on the set of property classes.

A number of formalisms have been used to try to capture such relationships.

Actions upon Objects

It is not sufficient to define the set of objects and the relationships between them. We also need some way of accounting for the model's 'dynamics'. That is, some way of propagating changes in the model's details through time. Thus we also need something akin to operators that act on, and transform, parts of the model's structure. We will assume, for the moment, that these operators can be captured in some procedural way.

We need to be careful as to what procedures are to do. We might imagine them to be context sensitive operators that change a model's state. This, however, does not necessarily mirror the way 'nature' works. Perhaps it would be more accurate to say that it is not necessarily the story we normally tell about what goes on as time passes.

Modelling a System

Let us suppose our task is to provide a model of a system from a kit of parts. We therefore have to construct the model by selecting instances of objects from predefined object classes together with their associated property classes and place them in relation to one another. These relations are instances of relations that are also predefined. This kind of modelling is discussed by Howe in relation to, inter alia, MECCANO [Howe 79]. Given a MECCANO kit, it is reasonable to assume that, in the construction of a model of a lift, it is necessary to select parts rather than to invent new parts. One also has to use the various means supplied to connect one part to another.

If the user, however, cannot see the analogy between MECCANO nuts and bolts and 'real' ones then the task cannot easily be completed. If the kit is not provided —or the wrong kit is available— then the problem becomes much harder and, on occasions, impossible in that no useful analogy may exist. One must expect, therefore, that such tasks may develop a better understanding but will not help the complete novice who has little idea about the nature of the analogy to be exploited.

In the context of LOGO we can see examples of such an activity when a student constructs a regular hexagon using a procedure to draw an equilateral triangle (called TRIANGLE) together with other predefined procedures such as FORWARD and LEFT.

```
REPEAT 6 TRIANGLE AND LEFT 60
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Of course, in this case it is very likely that the student also built the procedure for an equilateral triangle but for the moment we assume that this is not so. The student cannot be expected to construct a regular hexagon from the TRIANGLE procedure unless some clear notion is held about the way in which a regular hexagon is related to a regular triangle.

Modelling Relationships

Here again, we have a kit of parts. That is, we have a number of predefined object classes but this time we will assume that we already have chosen a set of object instances. The modeller has to invent relationships between the objects usually in order to compare the resulting model with the object modelled. An alternative and slightly simpler task is to alter an already existing relationship. An example of such an approach is the program WORLDS produced at Irvine as part of the "Science Literacy in the Public Library" project to investigate the use of stand-alone CAI programs [Bork et al 82]. In this program the user can try out a number of different 'laws of gravity' for a two body situation.

Modelling Objects

With this activity we have a set of relationships which may be potential rather than actual and we may also have an actual system constructed which entails that certain objects exist in a variety of relationships to one another. What is being modelled is the set of properties that any given object is to possess. At the simplest level, we may only be interested in changing the value of some property but we must be allowed to create instances of properties from some class of permitted properties. This is, essentially, creating new instances of an object or creating new object types.

For example, in the case of two body motion subject only to Newton's Law of Gravitation we may alter the value of the mass of one or both bodies. This level of modelling can be thought of as the approach closest to that normally associated with the exploration of a simulation. Throughout, it is intended that a simulation is to be understood as the *activation* of an underlying model. Thus simulation is a necessary part of the modelling process. It is also necessary to be aware that the modeller may well run his/her own simulation of the model before the computer runs its simulation.

A more complex and difficult aspect of the above type of modelling involves the creation of instances of properties which must fall within the scope of previously defined relationships. For example, assume that we are modelling the emotional behaviour of someone named "Fred". He is an instance of the object class of people and he may be assigned a phobia from the set of all known phobias. Thus Fred may possess "fear_of_spiders". Complications set in if the phobia instance contains extra qualifications such as Fred has "fear_of_spiders (little red ones)".

1.2.3 Modelling and Learning

Underlying any computer system that is intended to have an educational rôle are some assumptions about the way students learn. We will look at a number of issues applicable to the effectiveness of any system which claims to help students to learn. We are interested in the work of educational psychologists and their interest in both pedagogic issues and how children learn. We are also interested in approaches to learning recommended by Cognitive/AI Scientists.

Theories of Learning

From a Piagetian point of view, if we are to use a model then we must consider the relationship between the complexity of the model and the developmental stage of the student. If we take into account the results of research into the relationship between age and the developmental stages attained then we must expect problems with the introduction of models that are too abstract [Shayer 72, Shayer & Adey 81].

There is a difficulty in specifying what might be meant by the level of abstraction of a model. Following Lovell [Lovell 74], one can apply such an idea to individual concepts but there is little evidence that one can make any meaningful assessment of the overall model. For instance, a given model might contain some features that would have to be judged as requiring the ability to perform formal operations but this does not automatically invalidate the use of this model for teaching purposes since one may be able to exploit the other features in a way that requires a less abstract level of response from the student. This seems to lead to the idea of using parts of models but we must assess this in relation to the dangers associated with modelling in the classroom.

There are other theories of learning which might be mentioned briefly. Ausubel maintains that a new topic must be introduced by means of advance organisers [Ausubel et al 78]. It is maintained by Ormerod that models can be used as advance organisers [Ormerod 78] although the idea needs further clarification. Bruner's theory of instruction has also been investigated. He suggests that there are three stages which children go through to master a topic. They are, in order, the enactive, the iconic[4] and the symbolic [Bruner 66]. Gee sees the iconic stage as appropriate for the introduction of, naturally enough, iconic (analogue) models [Gee 78] but research by McIntyre [McIntyre 74, McIntyre & Reed 76] is surprisingly inconclusive about the effectiveness of Bruner's scheme.

Another, process oriented, view of learning is described in terms of accretion, tuning and restructuring [Rumelhart & Norman 78]. Very loosely, accretion and tuning refer to the accumulation of data and to the slight adjustments that need to be made to the existing cognitive structure. Restructuring takes place when the existing structure cannot accommodate the new data without making major alterations to the relations between concepts within the structure.

In these terms it becomes reasonable to expect students who can reflect on their own activities to have an improved chance to restructure their system of beliefs. For example, in an electrical circuit modelling system, students will

[4]i.e. analogue.

have evidence in the form of a circuit specification, data output from the circuit analysis and some explicit goal that they wish to satisfy.

Alternative Frameworks

It is reasonable to suppose that there is a psychological value in using models but this value must depend to some extent on the internal state of the student. What the student believes will influence what s/he finds to be an acceptable model. Here, we begin to take the student's "alternative frameworks" into account (see [Driver 81]).

Several workers see a distinct advantage in getting students to make their own assumptions explicit (eg [Clement 82, Driver & Easley 78]). This is of particular advantage when it is believed that the student possesses an informal or incorrect formal model of the situation which needs to be confronted before the correct formal model is acceptable to the student.

An explicit description of a situation by a student should enable the teacher (or program) to choose ways of presenting the student with problems relevant to the student's failure to solve a given problem.

After the student has collected new evidence and after s/he has sought to reconcile prior beliefs with the new evidence (if this is felt to be necessary) then s/he may find that a new model —possibly provided by another person— will act as a *post organiser* and lead to a more reliable model.

The view of Pask [Pask 76], which is assumed throughout, is that the understanding of a concept includes the ability to execute a variety of procedures successfully. If the student executes some procedures and they behave in ways different from the commonly accepted procedures for the given concept it is possible to automatically detect some of the major problems that the student has. An example, which will be explained in more detail later on, can be seen in diSessa's report on the work done by some 6th grade students with the DYNATURTLE [diSessa 82] in which he states that these students demonstrated distinctly non Newtonian ideas about bodies in motion.

Problem Solving

It is intended that students be given the freedom to build models but they must also be motivated. The ensuing style of learning can be described as an example of learning by discovery. One of the reasons why learning by discovery has 'had a bad press' is a consequence of the difficulty of providing students with a set of goals which are relevant and achievable —or of the student generating them from within.

If the student can adopt a goal that is relevant and seen to be so by the student then s/he may be able to learn a great deal through the problem solving which will be needed in order to satisfy the goal. On the other hand, it is possible that the student will focus on the problem solving issues that arise to such an extent that s/he will not notice —or will fail to remember— important domain specific facts/principles. This point will be discussed further in the next chapter.

The problem solving approach recognises the need to engage the attention of the student over a fairly long time period in comparison with, for example, some drill and practice arithmetic program. This longer time span has the potential advantage of allowing the student to form a clearer impression of how, and in what circumstances, various principles and facts of a theory are applied.

The aim is to encourage the various transitions which turn the 'novice' into an 'expert'. For example, we have to encourage the building of plans which permit the rapid solution of problems.

It is an implicit assumption of the problem solving approach to learning that failure forces students to learn. This further implies that the student has to have good feedback and 'model debugging' tools. We are all too familiar with some of the CAL programs which handle a wrong answer by revealing little, if anything, of the structural detail of the skill that is being learned but is faulty:

> Computer: What is 3+4?
>
> Student : 6
>
> Computer: No, the answer is 7.

The requirement of good feedback implies that we provide the user with a set of error messages associated with the appropriate 'real world' events. Ideally, the error message should be couched in terms that the student would use to describe the event. Thus a circuit that had no current flowing in it would have to report this —provided, for example, the student associates the word 'flowing' with the concept of current. We are under a strong obligation to keep in mind the student's own conception of current. The idea of error messages should be generalised to that of an 'event' message which reports on various sorts of error, on occasions for which there is normally no visible sign of success and other 'interesting' occasions.

Can we outline a large enough set of design principles to construct programs that will encourage students in their problem solving? Can we show how different students respond to such a program and demonstrate any improvement in their (general or specific) problem solving abilities? Some attempts that are relevant have been made[5] but we do not pursue the matter here.

1.2.4 Modelling as a Substitute for Experimentation

The activity of modelling entails setting up experiments as a means of debugging the model built. It must be pointed out that the process of building models is not always distinct from that of testing and using them.

Some have maintained that experiments should always take place in the 'real' world. Sparkes, for example, maintains that 'real' experiments should always be performed where possible and he goes on to point out that a computer simulation of real world phenomena is the realisation of the programmer's model of the relevant phenomena [Sparkes 82].

One cannot doubt the validity of this point of view but there is much more to be said about the educational value of constructing models and testing them

[5] See [White 81] for details of an example.

both before, during and after a formal study of the phenomena themselves. After all, it is commonplace for teachers to provide students with theoretical models prior to experimentation.

There are three reasons why 'real' experimentation might precede some form of modelling: firstly, the student may need to gain some informal expectations about the flow of events. Secondly, the student may have a set of natural expectations which are known to be contradictory to experience. Thus attention may have to be drawn to a particular set of experimental results. Thirdly, the teacher may believe in the 'Baconian' method of collecting data before any hypothesis is constructed. We do not seek to use the computer to usurp the place of experimentation in the school curriculum. Rather, we would place more emphasis on the benefits of the student both building explicit models and examining the consequences.

If the computer's value is seen to be lessened because it deals with a model of reality rather than the appropriate reality itself then one should bear in mind the move away from the view of the scientist as a *tabula rasa* collecting data prior to some analysis. Whether one sees things in Popperian or Kuhnian terms it is now generally accepted that observations are not hypothesis free. That is, the hypotheses (or beliefs) that the scientist holds about the world conditions both the type of experiments performed and the nature of the observations made. The computer offers the opportunity to grasp the nettle of the distinction between the world and our beliefs about the world and make far more explicit usage of the idea of the scientist as an explorer of some model of the world.

Perhaps it is now appropriate to give the standard list of advantages in using computers:

- *Experimentation is too dangerous*: The student can do things without any fear for his/her safety and the system can point out (some of the) dangerous activities —such as short circuiting a battery

- *Experimentation is too expensive*: In terms of money, time etc.

- *Experimentation is impossible*: Investigating alternative worlds —one could experiment with alternative versions of, for example, Kirchhoff's Current Law or a different version of Newton's Second Law. There are, however, severe problems in replacing such global laws in any meaningful way.

- *Experimentation is difficult*: Due to problems of space, time etc.

Some (or all) of the above are applicable to the systems that are described later but such advantages do not provide sufficient justification for the activity of modelling. Some small justifications can also be provided as we also have the possibility of:

- *Handling sensibly the problem of measurement:* The principles of measurement can be gradually phased in so that the student is not overwhelmed by a mass of detail about the usage of meters, rulers, units etc. This is an example of a more general advantage in that complexities can be added in a more principled way than is usually possible in the classroom.

- *Replacing some experiments and exercises:* Some demonstration experiments and some of the pencil-and-paper exercises often utilising formal algebraic skills can be replaced. A more practical approach to solving physics problems has advantages over methods requiring formal skills in manipulating complex algebraic equations (see [Champagne et al 80]).

1.2.5 The Inevitable Risks

The pedagogic advantages of using analogue models are not as overwhelmingly convincing as one would like. The student is not an experienced scientist so one must approach the idea of using models with caution. Although there are advantages in using models to assimilate new concepts there are dangers associated with this. Let us look briefly at the known problems that are in store for the student who is building a model.

One of the 'classic' mistakes is to take the model for the real thing. An example is the way in which the fluid flow model of electricity has resulted in students talking about current flow [Harré 78]. The strength with which some students believe in the flow of electricity has been noted by Evans [Evans 78]. Another related mistake is to identify an analogue model of a formal theory for the theory itself. Thus the billiard ball model of the kinetic theory of gas can come to be mistaken for the kinetic theory itself. Given that one of our aims must be to alert the student to the distinction between the model and the thing modelled these kinds of error are serious.

There is also a tendency for students to be distracted or influenced by features of the negative analogy. Here, we must be careful. The very fact that they are distracted by some feature of the known negative analogy suggests that the student does not know that the feature is part of the negative analogy. Thus, in the case of the billiard ball model of the kinetic theory of gas, it is quite possible that the student might wonder about the colour of a molecule of oxygen or whether one can scratch it. It is not obvious that such behaviour is to be discouraged —the task is to help the student to reevaluate the analogy. Following Hesse, we accept this danger with the qualification that there has to be a decision as to how to steer the student into constructive explorations based on a reassessment of the analogy.

Students are also found to mix their analogies. This would seem to be most likely amongst those who are still struggling to construct a coherent account of the phenomena and are still trying to assimilate technical terms and fragments of explanations offered by teachers. It is the task of the teacher (or program) to help the student to form a clear internal model (or models).

Further, we know that it is frequently found that a student will cling to the most rudimentary of models which may well be the first one of several increasingly powerful models of a phenomenon. This behaviour can be seen as a special case of applying an inappropriate model to a situation. Again, it is the task of the teacher (or program) to help the student learn how to determine the inadequacies of the match between a model and the thing being modelled.

1.3 Modelling Environments

If we have a model interpreter and a number of objects, their relationships and the legal procedures then we must bear in mind that there may well be other ways of describing a model and other model interpreters. As Hayes has pointed out [Hayes 79], one might wish to use a variety of different representational systems such as KRL (see [Bobrow & Winograd 77]) although KRL does not include a model interpreter.

It is necessary to look at a number of important examples of modelling environments and see how they perform in relation to their potential for secondary school students to model misconceptions. The contenders include LOGO, Smalltalk[6] and THINGLAB.

1.3.1 LOGO

LOGO, for instance, enables one to build objects as a sequence of actions —it is a procedural language. The properties of the object underlie any particular sequence of activities that cause an instance of the object to be constructed. For example, figure 1–1 shows how we might convert some formal definition of an equilateral triangle into a LOGO procedure.

To produce the above procedure, it is necessary to know that a triangle has three sides. It is possible that someone who did not write the procedure could recover this property from the list of activities that the computer performs when the procedure TRIANGLE is run. Thus the property classes of the object are implicit. LOGO, therefore, is an example of an approach to modelling that does not fit in with that outlined in the previous part of this chapter.

[6]There are several distinct versions of Smalltalk —the latest being Smalltalk-80. See [Goldberg & Robson 83].

```
TO TRIANGLE 'SIDE

FORWARD :SIDE
LEFT 120
FORWARD :SIDE
LEFT 120
FORWARD :SIDE
LEFT 120

END
```

Figure 1–1: LOGO Definition of TRIANGLE

1.3.2 THINGLAB and Smalltalk

If we turn to THINGLAB we have a different situation [Borning 79]. THINGLAB is a *simulation laboratory* written in Smalltalk [Ingalls 78]. Smalltalk is an object oriented language in that we create an object by explicitly declaring its internal properties, the nature of the messages which the object can receive and send and the methods that the object has for processing messages. Objects also inherit methods and properties from the class to which the object belongs[7].

Defining an object in THINGLAB is very similar to defining an object in Smalltalk except that we can also specify certain constraints. Figure 1–2 shows a definition of a *triangle* class using THINGLAB.

One can immediately see that a triangle is built up from three lines and that certain constraints tie the lines together in a particular way. This seems very

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[7]Each object belongs to a particular class which is also a Smalltalk object. There is, however, a 'root' class which, though treated as an object, does not belong to any other class.

Class Triangle

Superclasses

Geometric Object

Part Descriptions

Side1: a line

Side2: a line

Side3: a line

Merges

Side1 point1 = Side3 point1

Side1 point2 = Side2 point1

Side2 point2 = Side3 point2

Figure 1–2: THINGLAB Definition of TRIANGLE

close in spirit to the outline definition given to models above. One point seems worth mentioning: how difficult would it be for an average secondary school student to build this definition? The task is very abstract when compared with the simpler LOGO task of constructing a procedure for an equilateral triangle. For example, it is not clear how well students can cope with the inheritance mechanism of Smalltalk.

Nevertheless, the Smalltalk object oriented approach seems to have much to recommend it. We may imagine a set of objects in a number of relationships with each other —some of which may be in the form of constraints. Each object is able to act upon other objects by means of the procedures (in Smalltalk, the methods known by the object) to which the object has access and the message passing mechanism. This permits us to imagine a form of causal chain of events which may account for the normal physics account for how the thing modelled changes with time. There is a strong Smalltalk flavour to the underlying philosophy of the systems described later.

Unfortunately, this approach may fail in a very common situation. It is not easy to see how we are to model phenomena that are normally described as continuous —such as the electric field or the gravitational field. We could, of course, postulate abstract objects such as a gravity-field but we will need to define both the part that individual, physical, objects play in creating the abstract object 'gravity-field' and how the gravity-field object influences the physical objects. We must say more about this when we come to discuss the problems of modelling.

1.4 Misconceptions

During the last ten years or so there has been an increased interest in examining the belief systems that children bring to the investigation and learning of science topics. Why is this so?

The science education of students is influenced heavily by some current view of the learning process. One idealised assumption might be that students have all the intellectual equipment required to learn everything taught. Their only problems arise if, for example, a topic is taught which requires some skill that has not been taught —and therefore not learned. This assumption seems to underlie the method in which an analysis is made of a difficult topic in order to produce the *best* sequence of teaching material. Gagné, for example, recommends the construction of a *Learning Hierarchy.* Such a hierarchy defines a set of skills that the learner has to master in order to be in a position to learn the (single) skill for which the hierarchy has been constructed. The set is given further structure by requiring that no skill should be learned before any skill upon which it logically depends [Gagné 77]. Various attempts have been made to show that it is possible to construct a Learning Hierarchy that is valid [Linke 75, White 73, White 74].

There is no disputing that such an activity must be undertaken —perhaps as part of a wider venture designed to capture the mesh of skills that are required for a large domain. In recent year, however, an increasing number of studies have emphasised the need to take the cognitive structure of the students into account. In part, because students have a fairly stable set of beliefs about the real world which are extremely difficult to uproot by teaching or by simple observation [Nagel 61].

These studies are of a number of kinds. Often, their ostensible goal has been concerned with the domain and aspects of the student's cognitive structure have emerged in the course of the work.

1.4.1 Identification of Difficult Topics

A number of studies have sought to identify areas of difficulty in the secondary school science curriculum as a prior requirement for further research. Essentially, these indicate topics which may be difficult because of some mismatch between the capabilities of the students and the material or the way in which this is presented. Some analyses have concluded that part of the reason why these topics are difficult is due to the prior beliefs of the student [Fisher 79, Howe 80, Howe 83, Johnstone & Mughol 76].

1.4.2 Construction of Tests

Having identified a number of specific difficulties that students might possess, various attempts have been made to demonstrate the widespread nature of these problems by means of tests designed to be applied to large numbers of students. Such tests often have a broad focus in that they try to demonstrate that certain problems are widespread in terms of nationality, age and ability [Doran 72, Helm 80, Siegel & Raven 71, Za'Rour 75]. Inevitably these tests of themselves provide little insight into how certain beliefs arise or how to alter them.

1.4.3 Developmental Studies

Some reference must be made to the large number of studies that Piaget undertook in pursuit of his interest in genetic epistemology. The Piagetian research program attempts to uncover the steps that students take in reaching some increased understanding or level of performance. The fundamental methodology often requires that students be observed individually or in small groups as they try to solve some problem or perform a task presented by the researcher. A by-product might be a description of the classes of problems that students may have at certain points in their cognitive development. The aim of such research, however, is to provide a consistent account of the growth of cognitive abilities.

In the narrower context of secondary level science education, there are a number of workers advocating a constructivist approach to how students learn science [Driver 81, Driver 83, Osborne et al 83]. Various terms are used to describe the student's cognitive structures. The most common of which are *Misconceptions*, *Alternative Frameworks* and *Children's Science*.

1.4.4 Some Definitions

It is possible to spend a fair amount of time in carefully distinguishing between the three terms in section 1.4.3. In this work these terms will be conflated and referred to under the single term *Misconception*. A brief description of the three terms follows:

Misconception A wrong conception. There is a suggestion that the person possessing the misconception is absolutely wrong. There is a hint that certain beliefs might be held as logical propositions.

Alternative Framework A complex structured set of beliefs which have often been plausibly inferred through experience of the real world. Driver is strongly associated with expounding the implications of such structures [Driver 81].

Children's Science A distinction is made between Children's Science, Scientist's Science and Curricular Science. Children's Science, according to Osborne et al. [Osborne et al 83], is

> the views of the world and the meanings for words that children tend to acquire before they are formally taught science

The approach seeks to take seriously the belief that children must start with their current set of beliefs and transform them into beliefs more in accord with commonly accepted scientific notions.

There is growing support for a confrontationist approach in which the differences between children's beliefs and strategies (children's science) are to be confronted directly [Zeitman & Hewson 86].

1.4.5 A Very Brief Survey

A fair number of studies have now been made of children's scientific misconceptions. The domains that have attracted interest most strongly appear to have been Newtonian dynamics[8] and simple electrical concepts. The interest in these two areas was a major factor in the choice of domains in which to apply the various ideas discussed in this thesis. Further discussion about the various misconceptions found will take place in later chapters.

It would not be fair, however, to suggest that these two domains are somehow special. Studies have been made in the areas of heat [Erickson 79], the nature of the planet Earth [Nussbaum & Novak 76], the concept of Plant [Bell 81], floating and sinking [Rowell & Dawson 77], light [Watts 85], energy [Soloman 83], gravity [Ruggiero et al 85] and so on.

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[8] Including kinematics.

1.5 An Outline of the Thesis

1.5.1 The Contribution of the Thesis

In very general terms the thesis makes a number of contributions to the understanding of the ways in which computational modelling environments can help secondary school students learn physics concepts.

Educational Aspects: A clarification of the educational advantages and disadvantages associated with students modelling physics situations. This incorporates a number of points relevant to the construction of physics curricula, classroom practice and management of the student's learning.

Misconception Analysis: A collation of common student beliefs (misconceptions) in two different domains, an analysis of how these might be placed in a single framework and the implications for students modelling physics situations.

Modelling Analysis: An analysis of those aspects of modelling which can be well supported by computational environments and the aspects which are very difficult to support.

A more detailed description of the contributions of this research can be found in chapter 6.

1.5.2 The Structure of the Thesis

The thesis is divided into six chapters. The current chapter has set up the basic goal of the research and outlined the three essential components: the importance of modelling activities, the need for modelling environments and the significance of the student's misconceptions for the enterprise.

Chapter two sets out to explain the methodology used. This includes a discussion of the starting place of the research, by what means ideas were tested out with students and the rôle of evaluation.

Chapter three introduces the first environment built called ROCKET and describes some observations of students using the system. This work focusses attention on certain misconceptions that appear to be commonly held about simple dynamical situations and a discussion of the advantages of modelling over straight simulation programs. Chapter four continues by concentrating on the design and implementation of a modelling environment called DYNLAB. This provides a simple dynamics laboratory in which a number of critical experiments can be performed. Again, discussion includes reference to the experience of students using the system.

Chapter five introduces the problem of providing similar facilities for simple electrical circuits. The result is the design and implementation of a simple electrical circuit laboratory called ELAB. Further trials with students are combined with an analysis of ELAB's shortcomings. Chapter six provides a new design for ELAB which incorporates extra facilities. The possibilities of providing powerful automated assistants are considered along with concluding remarks on the future of such systems in the context of Artificial Intelligence research and Educational issues.

Chapter 2

Methodological Issues

2.1 The Selection of the Initial Domain

The methodology adopted was to start by developing a system which exploited work already done. The requirements for such work were:

- Should feature the use of computers
- Should feature a modelling environment
- Used in some domain of physics
- Used with secondary schoolchildren
- Used for investigating misconceptions

2.2 The Work Done at MIT

The starting place was based on the work of diSessa at MIT who describes, inter alia, a program called TARGET [diSessa 82]. This program was investigated within the context of the Brookline Project which was an attempt to evaluate the effect of providing 6th grade elementary school children with the programming language LOGO [Papert et al 79].

The LOGO language incorporates various drawing primitives organised around the concept of the "turtle" which is a small object with a position and a heading that can leave a track as it moves across the screen. The commands that change the state of the turtle produce motion relative to its original state. These commands are LEFT, RIGHT, FORWARD, and BACKWARD and all take a single numerical argument.

The DYNATURTLE of diSessa is an extension of the idea of the turtle in that the state of the turtle incorporates its velocity as well as its position and heading. The commands that change its position do so by changing its velocity and therefore its position indirectly. The commands that change the heading are L for LEFT 30 degrees, R for RIGHT 30 degrees and the command that changes its velocity is K for KICK one unit.

About six students were each given up to ten hours with the DYNATURTLE in which they were asked to hit a target with the DYNATURTLE moving as slowly as possible. The DYNATURTLE starts from rest and the target is 45 degrees from the heading of the DYNATURTLE. An analysis of the students revealed some interesting tendencies. In particular, the students tried a particularly *Aristotelian* strategy of kicking the DYNATURTLE when it was pointing toward the target and still moving with a component of velocity at right angles to the target's direction as shown in figure 2–1.

The DYNATURTLE fails to go in the direction of the target. This is evidence for the belief that a body moves in the direction of the applied impulse rather

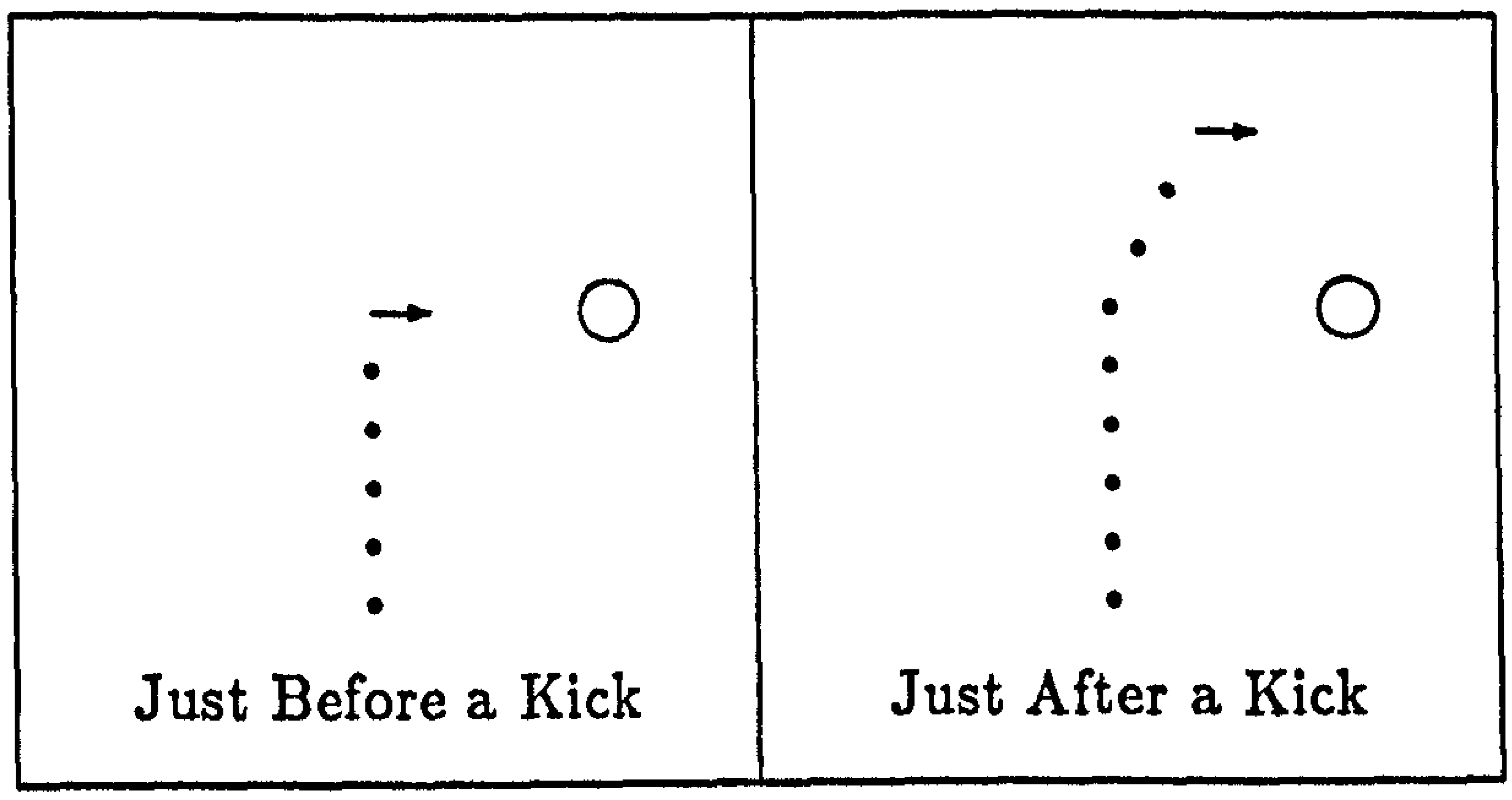

Figure 2–1: A Naive Expectation

than the belief that the change in velocity is in the direction of the applied impulse. It was reported that almost every student in the sample tried this strategy at some time and that a common reaction of the students was that the computer had broken.

An analysis of a protocol of 24 games of TARGET taken from a freshman student with a year of high school physics and nearly a term of college physics showed certain similarities between her play and the results obtained from the younger students. One result was the production of a *Genetic Task Analysis* which illustrated the kind of progress that a student could make through playing the game.

2.3 More on the Initial Domain

The work at MIT met the initial requirements well. diSessa had used a computer environment to focus on some misconceptions that 6th grade children (roughly equivalent to S1 children in Scotland) had with simple dynamics. This research also suggested that the environment was applicable to older students (see [diSessa 82]). The only deficiency was that the students did not build models and test them explicitly; the environment is not a modelling one.

It was decided to produce a similar environment and add a simple programming facility. The students would be able to drive the DYNATURTLE interactively or through a very simple programming language. This paralleled work with LOGO as it is often thought that children should start by driving the turtle with direct commands before starting to program with a small subset of LOGO commands.

Strictly, the programs would not be models of either the dynamics involved or the naive beliefs of the students. These programs might, however, reflect the beliefs of the students in a clearer way which might yield some interesting results.

After producing an environment based on the work of diSessa a first attempt would be made to create a modelling environment which would make a large number of the known dynamics misconceptions modellable.

2.4 The Selection of the Final Domain

As stated in the previous chapter, the target was to produce a design for a system to be applied to the domain of simple electrical circuits.

Therefore, the aim was to take the work done in the initial domain of dynamics in terms of the design of the modelling environment and the results obtained from observation and apply them to the design of a modelling environment in the domain of simple electrical circuits.

2.5 The Target Population

For a number of reasons, the target population was chosen to be secondary school students in S4 and S5 —which, in England, is equivalent to Fifth and first year Sixth form levels respectively.

The relevant factors to take into account include:

- In piagetian terms, some of these students are likely be at the transition stage between operational and formal levels of thinking

- In terms of their past experience of physics, they have been exposed to a large number of physics concepts, methods and so on

2.6 The Place of Evaluation

There have been quite a few applications of Artificial Intelligence techniques and ideas that are of interest to those in the educational world. The motivation for such applications has often included a strong desire to improve the educational process in some way. Great claims have been made on occasions such as, for example, children learn generalised problem solving skills better in the LOGO environment than in others.

It is necessary to bear in mind that some of these claims may well be side issues for the original researchers. Quite legitimately, they may be more interested in continuing to tackle hard AI problems than validating their beliefs about the educational advantages that accrue from their research.

Educationalists, however, require a number of answers to questions that have not often been asked in the AI context. Here is a small selection:

- Can the usage of some new system be accommodated within current curricula?

- How should teachers be trained to take advantage of new opportunities?

- What management skills are needed by classroom teachers?

- What are the benefits and the disadvantages for the individual learner?

The educationalist requires some form of evaluation which will help to answer the above questions and others. It is therefore necessary to consider the part which evaluation should play in this thesis.

The educationalist often requires a formal evaluation in order to decide whether to pursue the further development of a piece of research. The reason, ultimately, may be to locate the developed product into the school curriculum. In practice, there may be a choice between a formative or summative method of evaluation. To paraphrase Scriven slightly, a formative evaluation assists in the creation of a product while a summative evaluation helps in the assessment of the final merit of a product [Scriven 74].

The work described in this thesis does not attempt the development of a finished product. Therefore, any (summative or formative) evaluation generally lies outside the scope of the research described herein. The thesis contributes an outline of a particular usage of computers which entails some conclusions that might well be substantiated in some later educational evaluation. Nevertheless, evaluation has a rôle to play.

One of the consequences of advocating modelling as a means of learning about physics is that the cognitive processes involved have to be taken into account. In particular, if there are benefits from the approach outlined in this thesis then a start must be made to map out the skills which are necessary to use such computer systems. Indeed, it is necessary to know which cognitive skills are encouraged and which are discouraged. Therefore a method of evaluation is required in order to provide a sketch of the processes involved in the use of the various systems. In particular, there are a number of interesting general questions that will surface now and again:

- What syntactic features cause problems and do they reflect some deep conceptual misunderstanding of either the system or some physics principle?

- How well do students set up critical experiments that test their understanding and what support might be helpful?

- How well do students interpret their results?

- What is the surface evidence for deep misconceptions and how reliable might such evidence be?

An illuminative evaluation is required. Nevertheless, a full illuminative evaluation requires retrieving information from a large number of sources. Some of the possible sources of information were finally rejected in favour of those which are described in section 2.7 which follows immediately.

2.7 Observational Strategies: Feedback from Modellers

One of the goals might well be to sketch out a map of the cognitive territory that applies. Such a concept map could be a semantic net, a procedural net or, more probably, some complex mix of both. Definitions of *concept* include "an abstract object" to "a general idea of something formed by mentally combining all specific parts and characteristic features" [Collins 79]. As has already been pointed out in the previous chapter, Pask effectively extends the definition by associating a concept with entities which have a procedural (skill) element [Pask 76]. In the AI field, there has been a number of attempts to represent 'concepts' with a variety of formalisms[1].

The techniques needed to construct some conceptual map are various and have included introspection, knowledge elicitation through interviewing techniques, questionnaires, repertory grid techniques, passive observation —each method usually requiring a great deal of further analysis on the resulting data.

Word association tests, for example, became common from about 1965. Some of this work bears directly on the increase in understanding of the problems that students have with mechanics [Johnson 64, Johnson 65, Johnson 67, Johnson 69], [Kass 71, Shavelson 72, Shavelson 74, Preece 76]. Most of the conclusions from this research do not attempt to map an individual's cognitive structure but reveal very *grainy* maps that represent some kind of consensus view.

[1]For example: full first order predicate calculus, frames, semantic nets etc.

The work underlying BUGGY [Burton 82], for example, resulted in a very detailed analysis of the ways in which a map of the skills associated with the concept of subtraction might be put together. This work depended to a great extent on the hand analysis of a large volume of students' attempts to do subtraction sums.

So there are a number of options as to how to find out what we want to know about the ways in which students use the modelling facilities provided. Those considered include:

- Tests
- Questionnaires
- Protocol Analysis

2.7.1 Tests

A number of tests have been designed to assess the performance of students on a representative range of science reasoning tasks. A good example is the test devised by the CSMS (Concepts in Secondary Mathematics and Science) project [Wylam & Shayer 80]. It would be a reasonable candidate for a means of validating any putative improvement in general science reasoning.

On the whole, the research into the problems of learning both electricity and dynamics is still an exploration of the territory. The problems are often perceived in domain dependent terms which are difficult to relate to various generalised science reasoning abilities. Consequently, it was decided not to incorporate any such tests into the research.

Testing, though, has a number of functions including:

- Detecting an improvement in a treatment
- Discriminating between treatments

- Determining whether some topic has been mastered

- Discriminating between individuals

The main interest did not lie in any of the above objectives. Rather, some tests —in a very loose sense of the word— were sought that would pose a set of problems known to be difficult. The solution of each problem would be within the grasp of each student in principle. That is, the student would have formally covered the ground in physics classes. An additional, and important point, was that the solution of each problem should be associated with at least one potential misconception. This was to ensure that students be placed in predicaments where, if they have a misconception, they might well produce an incorrect answer. Finally, a completed test would be used in two ways: as a pencil and paper test and as the basis for the modelling that the students would engage in with the help of the various modelling systems.

This scheme of work suggests that the test should be considered as a pre-test and the modelling work as the treatment. This raises the question as to whether a post-test should be designed to assess any improvement after treatment. It has already been stated that such a scheme has been ruled out. Nevertheless, it is worth giving some of the reasons why a post-test was deemed impractical for this research.

The first point is that the obvious post-test would have been very similar indeed to the pre-test. This is primarily because the work is organised so closely around specific misconceptions. It would be very surprising if such a post-test had not shown an improvement in the students' performance overall. The second point is that any improvement in the students' performance would only be worthwhile as a long term improvement which has the implication that any such evaluation lies outside of the time available for the research. The design of a suitable post-test at some more abstract level is possible but lies outside of the scope of the thesis.

2.7.2 Questionnaires

Although questionnaires have a rôle to play in gathering useful illuminatory material little use was made of the technique until observations were made on the use of the electrical circuit modelling facility. The questionnaire was designed: to draw out some of the modelling background that the students thought they possessed and to determine how students felt about their physics work.

2.7.3 Protocol Analysis

For the most part, attention was focussed on protocol analysis as a means of getting data for later analysis. There are a number of possible approaches including:

- Verbal protocols
- Written protocols
- Dribble files —i.e. a complete record of student's interactions with the machine

Dribble files were kept for each of the three systems built[2].

Passive verbal protocols were only taken for the work with the electrical circuit modelling system. Each session of work was recorded for later analysis. One set of interviews was made with the physics teachers of the students at Daniel Stewart's and Melville College, Edinburgh.

A little written material was obtained from the worksheets which were an integral part of each of the three systems.

[2]The Apple Computers used had no clock so timings were not kept.

Chapter 3

Observations on Misconceptions

3.1 More About the Work at MIT

One of the chief aims of diSessa was to construct a task analysis of how players of TARGET learn to understand Newtonian dynamics. The result is a *genetic* task analysis because it attempts to provide an account of how the novice might use DYNATURTLE as a means of learning Newtonian dynamics (see [diSessa 82]).

He outlines both what he believes novices learn through DYNATURTLE and how this knowledge might be used to further the transition to expert.

White takes this work and produces a number of design principles which are developed in parallel with eleven computer games [White 81]. In particular, she observed 21 students at High School level playing the 11 games and answering a set of questions designed to test their understanding of dynamics. She also switched contexts from that of LOGO and the DYNATURTLE to a spaceship free of the influence of gravity and friction. One can interpret the games as a means of focussing on the steps required to traverse diSessa's *Learning Path* chart[1]. She sees the games as:

> The games then encourage what has been termed the scientific method: the process of forming a hypothesis, testing it, getting feedback and modifying the hypothesis to fit the results.

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[1]See appendix A.

The work described in both this chapter and the next was aimed at making the hypothesis more explicit.

Basically, diSessa reported work related to one particular non-Newtonian conception prevalent among a number of children and college students. White, however, was able to make a more detailed analysis and found some other problems: given the task of getting a stationary spaceship to go as fast as possible in the direction in which it was pointing, some students gave one kick and then could not see how to make the ship go any faster. Any extra kick would make no difference! Another interesting conclusion is that a kick perpendicular to the path of a moving spaceship is often seen to leave the speed unchanged.

3.2 The Design of ROCKET

The design of ROCKET is based on the description of TARGET given by diSessa [Papert et al 79, diSessa 82]. Some changes were made. Both the changes themselves and the reasons for them are detailed later.

3.2.1 Educational Objectives

The high level educational objective was to produce a program which might enable S4 and S5 students to come to terms with Newton's Laws of Dynamics. The program went through the cycle of:

Development⟶Class Trials⟶Revision

and, after further trials, the program's shortcomings became clearer.

The explicit educational objectives included:

1. To familiarise students with a gravity free and friction free world
2. To emphasise that a body does not necessarily move in the exact direction in which it is pushed

3. To indicate that it is the change in velocity that takes place in the direction of the kick and that this change is proportional to the size of the kick

4. To show that the rotation of a body about its centre of gravity does not affect its velocity

5. To demonstrate that a body will maintain its velocity unless some force is applied to it —or, equivalently, unless some kick is applied to it

3.2.2 Outline of the System

ROCKET is a computer program written in APPLE PASCAL to run on an APPLE II computer with a language board. It was developed entirely by the author within the context of the "Learning Engineering Science by Computer" project run by the Department of Artificial Intelligence, Edinburgh University in conjunction with Bell College of Technology, Hamilton and jointly funded by the Social Sciences Research Council and the Scottish Education Department [Howe 80, Howe 81]. It was written in the Autumn of 1981 and used by students in the Spring of 1982.

The system provides an opportunity to explore a model of a particular physical situation. As the system provides little in the way of help to enable the user to learn the system itself or the underlying physics that is modelled, there are some worksheets that accompany ROCKET. The success of the educational objectives depends not only on the effectiveness of the system but also on the efficiency of the accompanying worksheets.

The situation modelled is that of a body moving in two dimensions not subject to gravitational or frictional forces. The body is capable of being rotated about its centre of gravity with no expenditure of energy. It can also be given an impulse (called a *kick*) but since there is no attempt to be realistic about the way the kick is implemented in terms of ejecting matter from the rocket the mass of the rocket is regarded as constant. The full extent of the simplification is now apparent.

The explicit objective presented to the student is to manoeuvre the rocket so that the target which is in the middle of the screen is hit. The student is able to turn the rocket 10 degrees at a time (either right or left) and s/he can also give the rocket a kick with a magnitude from 1 to 9 units.

A small programming language was included which allowed the game to be played in two ways: in the first *interactive* phase, the student interacts with the system to drive the rocket but in the second *programming* phase s/he has to write down a sequence of commands before seeing the result. Thus the student has to devise a simple plan to solve the problem that s/he has been given.

3.2.3 Further Details of the Design of ROCKET

The program is made up of a brief description of the game followed by the game itself.

Before each fresh attempt to hit the target the student is given a prompt. The student is told how to switch from one phase to the other and what keys to press to initiate appropriate activities. The student can also leave the program at this point.

The student now attempts to hit the target either by direct control or by running a simple program that the student has just written. During the first phase, the student can perform the following actions:

L Turn *L*eft 10 degrees
R Turn *R*ight 10 degrees
n Kick *n* units[2] —where n is from 1 to 9 inclusive

At any time the student can opt to write a small program to try and hit the target. This is a quite deliberate attempt to encourage the student to formulate

[2] A kick of one unit is sufficient to impart a change in velocity to the rocket equal in magnitude to some unit of *speed*.

an explicit plan. It was anticipated that one of the strategies used would be to write an almost correct program and then to modify it until it worked. This should involve a systematic attempt to hit the target by varying one line in the program at a time until the target has been hit.

When the student chooses the second phase, s/he is first given a brief explanation of the programming language:

W	*W*ait nn units[3] of time
L nn	Do a *L*eft turn of 10*nn degrees
R nn	Do a *R*ight turn of 10*nn degrees
K n	*K*ick n units
E	*E*nd the program

Also note that, for example, *L 5* is completely equivalent to pressing *L* five times in the first phase of the program. The student then enters a program and runs it.

Once the student has entered a program s/he will have no further opportunity to study it although it is possible to rerun it. Although it would have been easy to arrange for the system to hold the data and to provide a simple editor it was felt that students should be encouraged to maintain good work habits. Therefore, the decision not to offer these facilities was a deliberate attempt to force students to write down their programs on the worksheet before entering them into the computer. As the language is simple and no program can occupy more than twenty lines, it was hoped that this would not prove too tedious a task.

3.2.4 Worksheet Design

The idea, however, that the program could stand *on its own* in the initial trials was also rejected partly because the environment seemed far too unfocussed as

[3]The accompanying notes make it clear that nn could be $0 \rightarrow 99$.

an exercise in dynamics. Thus the program was equipped with worksheets in the hope that it might prove possible to see if the physical principles embedded in the program had been understood. The rôle of an interviewer was seen as being to find out the intentions of the student and to provide a focus for the student's attention. Worksheets, on the other hand, cannot safely be used to extract intentions but can provide a limited degree of focussing[4].

The program is provided with a set of Teacher's notes, a set of Student's notes and two types of worksheet. The first type is designed to help the student to make an initial attempt to control the rocket. The student is asked to describe the effect of his/her actions as this is seen as an important step in formulating a general strategy to hit the target. There is just one sheet to introduce the basic interactive commands.

The second type of worksheet refers to the programming phase. These sheets are used to encourage the students to write down their programs and to describe their behaviour. A variety of tasks are suggested which request answers associated with the physics of the situation. There is an introductory sheet, a summary sheet, four worksheets taking the student through the basic physics and some suggestions for some variations on the basic idea of hitting a target.

3.2.5 Reflections on the Design

Preliminary Design Issues

During the actual running of the program there are times when certain options are offered to the user and there are times when these same options are not available. The convention is that if an option is valid then it is offered to the user. In practice, it was found that the students did not pick up the convention automatically and one conclusion must be that such conventions should be spelled out clearly to the user and, preferably, that there should not be any divergence

[4]See the appendix B for some examples.

from this convention across the range of software to which the user has access. An alternative is that all commands are global and that each command has one basic effect —an attempt to issue a command in some state where the intended effect of the command is impossible to achieve for whatever reason should result in a message indicating the problem.

One of the major problems found in the early trials is associated with the strategy *trajectory* which consists of the student aiming the rocket at the target and kicking as hard and often as possible in an attempt to overcome the effect of a sideways component of velocity. Given the original geometry, it was decided to force the students to use smaller velocities. This is in line with the task set to the students using TARGET in that they were asked to hit the target as slowly as possible. To slow the students down, a maximum magnitude of velocity was permitted to the rocket. If this maximum were to be exceeded then the game would be over.

Another problem met was associated with the student's interpretation of:

R nn Do a *R*ight turn of 10*nn degrees

so a command of RIGHT 10 might be interpreted as a turn of 100 degrees in a single turn rather than ten turns of 10 degrees. This defect was remedied by defining the above command as:

R nn Do a *R*ight turn of 10 degrees nn times

It had been suggested that the students would be confused by the invisible multiplier of ten —for instance, the LOGO language has a command that looks rather similar. It was decided not to pursue this potential difficulty any further.

It was suggested that the students would have found the provision of a read out of the rocket's velocity of some use so this feature was added to the second version along with the necessary modifications to the notes.

The relevant documents were revised and an attempt was made to improve the layout of the worksheets as a response to the problem associated with getting the students to fill them in.

Criticism of the Second Version

The second version was tried out with the S4 and S5 students at Airdrie Academy as part of the research project outlined in section 3.2.2. Various further modifications were indicated or suggested by the classroom trials which must now be described:

1. It was suggested that it would be more interesting to the student if the rocket's initial position and velocity were to be varied. The merit of this approach is that the student would be able to test various strategies and examine their physical implications across a wide range of initial conditions. The present approach, however, can still be seen to have the advantage that the initial conditions of the rocket are reliable and therefore one can repeat an 'experiment' again and again. Any further modification of the program along these lines would need to take this factor into account.

2. It was felt that there was a need to emphasise the meaning of the display of the rocket's velocity. Since this meaning is clearly spelled out in the notes for version two, all one can do is to revise the associated notes in order to emphasise this point still further. Again, we can see that students cannot be relied upon to read notes. This does not imply, however, that we should not use notes since it is assumed that students should get used to referring to documents for information.

3. There were similar feelings about the order of the worksheets although the general layout seemed a little improved. In particular, it was suggested that worksheet no. 3 could well be removed and placed on a workcard for use as a reference while in the programming phase. A certain redundancy between the student's notes and the worksheets was also noted.

4. There seemed to be little or no difficulty in interpreting

   R 5

   as *do a clockwise turn of 10 degrees five times in a row.*

A further criticism can be levelled at ROCKET: why not show the relative position of the rocket in relation to the target? Now, showing the displacement from the target in terms of X and Y coordinates is not consistent with the means of controlling the rocket. This implies that there might be some benefit in giving one or both of distance and angular displacement. This was tried out prior to using the system with students and, although the evidence is anecdotal, it did appear that the distance readout contributed very little while the angular displacement readout made the game too 'easy'. As the criterion of ease is not necessarily useful if students are to learn the physics involved it does not follow that making the game easier hinders or promotes the desired educational objectives. Intuitively, the angular displacement readout led to simple feedback strategies with a reduced need to plan. Further experiments and analysis would be needed to determine how such a readout really affects students.

3.2.6 Classroom Management

The first version of the program was tried out initially by a number of S3 students at Airdrie Academy, Lanarkshire and, later, a second version was tried with some S4 and S5 students from the same school. The program was supplied with teacher's notes, student's notes and a set of worksheets (see appendix B for some sample worksheets).

One of the problems that soon became manifest is that this kind of program requires a commitment from the teacher to take advantage of the situation in order to explore the physics inherent in the situation. This is in sharp contrast to the tutorial program which allows the teacher to hand over the teaching to the program for some while. If we are to make use of models and simulations which do not have an explicit tutorial component then it is very likely that handing over such a program to a teacher is always going to be problematic. This raises the topic of teacher training which needs to be taken seriously if potentially open ended and complex systems are to be used effectively.

In addition, the students were reluctant to read the notes with which they were provided. This is not a new problem and its solution lies in the hands of the experienced teacher. As a consequence, the students did not all answer the worksheets. This can be attributed partly to the presentation of the worksheets which can be further improved. A factor in the success of the worksheets is whether or not the student expects that worksheets are an inherent part of the use of any such program and not a mere appendage. Without this expectation all such attempts to couple worksheets to the use of some computer program are likely to be unsuccessful.

3.3 ROCKET vs TARGET

3.3.1 The Differences

The following is a brief summary of the main differences between ROCKET and TARGET:

1. Turns of ten degrees were allowed rather than thirty degrees

2. Kicks of from one to nine units were allowed rather than only kicks of one unit

3. The initial velocity of the rocket was chosen to be four units vertically up the screen rather than TARGET'S zero velocity

4. The rocket's track was visible and the kick was displayed briefly

5. The target was of a variable size: if the student missed the target by going off the screen then the target was bigger next time (or, at least as big) whereas if the student hit the target it tended to be smaller next time

6. The second version of ROCKET did not allow speeds greater than twenty units: if the limit was exceeded the rocket blew up

7. ROCKET incorporated a programming phase

3.3.2 The Reasons for the Differences

Summarising the reasons or questions that underlie each of the above differences in turn:

1. Are the same effects observable with finer discrimination of angles? White suggests that her students found it difficult to operate with thirty degree turns owing to the supposed inability of students to differentiate between, for example, bearings of 030 and 060 degrees

2. Is the *Antikick* strategy robust? Was it found so frequently because the initial set up of TARGET made its discovery relatively easy?

3. diSessa chose to start the DYNATURTLE from rest; White also tried the variation of starting with a non zero velocity

4. It was hoped that marking the trajectory would help students reflect on previous actions in order to make corrections; White also chose to implement this feature. The momentary Kick was shown to indicate that an event had occurred on the screen

5. If a strategy works for a large sized target then will it work for the smallest size? This question provides some motivation for students to try the same successful (or nearly successful) strategy a few times in a row

6. In the pretrial, far too many students developed a strategy which comes down to saying that "if I point at the target and go as fast as I can then any sideways drift will be small enough to still let me hit the target" —so it was decided to prevent the occurrence of this strategy

7. It was hoped that it would be easier to spot strategies used when students needed to plan ahead without the help of direct feedback from the behaviour of the ROCKET

3.3.3 A Critique of TARGET

A claim has been made by Papert that providing students with such *microworlds* should enable them to learn by a form of discovery [Papert 71, Papert 80]. The discovery that takes place is either structured or unstructured. If it is structured then what are the critical features that provide the relevant structure? Does this structure come from within the student, from some teacher looking over the student's shoulder, from some written materials or some CAL package? One possibility is that the program can stand on its own as a self contained environment which has sufficient knowledge of the structure of the domain (in some sense) to reliably focus students on their possible misconceptions and difficulties. To do this, it is not sufficient to capture the structure of the domain and the likely difficulties that novices face. We also need a set of procedures and principles that can be used in the debugging process.

First, a trace of the processing that goes on might be considered desirable. One way is to give an interviewer the task of extracting protocols from students. It is possible that an interviewer simply observes and gives no guidance —but is this really the case? If a genetic task analysis is to be constructed then it might be important to ensure that, as a result of intervening, the wrong sequence of processes is not induced.

The investigations by diSessa indicate that the rôle of the interviewer is not a totally passive one even though it is stated to be a fairly non-committal rôle[5]. As a consequence, the *genetic* aspect of the genetic task analysis is in question.

ROCKET, however, was explicitly designed to be used without an interviewer and without any verbal protocols being taken. In this way, it was hoped to form some ideas about two things: whether diSessa's genetic task analysis fits unassisted student behaviour and the extent to which unassisted students could be said to learn physics.

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[5]For example, Jack, one of the Brookline subjects, did not spontaneously generate the concept of *Antikick* (see section 3.3.4) although some apparently did do so.

3.3.4 Automatic Strategy Detection

The program is set up to output data connected with the running of the program to a file known as the dribble[6] file. This file is a collection of two sorts of information. The first type of data refers to the commands given to the program by the user while the second type refers to a number of strategies detected by the program during the course of a game. The most important of these are listed below.

Before these strategies are listed it is important to make a distinction between the strategies observed by the investigators in diSessa's work and the strategies detected by ROCKET. In diSessa's work, the investigators were able to extract something of the intentions of the students so the categorisation of the strategies is in terms of these intentions. In the case of ROCKET, the strategies detected by the program must, of necessity, be in behavioural terms. This distinction must be borne in mind in any discussion of the results.

- *Aristotle Corner(1)* The rocket is moving and aiming at the target when a kick is given. At this moment, the rocket is pointing at right angles to its path. In TARGET, the strategy *Aristotle Corner* is the combination of both the strategy described here and the following one.

- *Aristotle Corner(2)* The rocket is moving and aiming at the target when a kick is given. At this moment, the rocket is not at right angles to its path.

- *Newton Corner(1)* The rocket is stationary and aiming at the target when a kick is given. The rocket is at right angles to its previous path. In TARGET, the strategy *Newton Corner* is the combination of both the strategy described here and the next one. This strategy seems to have been named *Newtonian* by default as it can be seen to work whether one is an *Aristotelian* or a *Newtonian.*

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[6]This name is used to indicate a file that keeps a record of all the student-computer interactions

- *Newton Corner(2)* The rocket is stationary and aiming at the target when a kick is given. The rocket is not at right angles to its previous path.

- *Antikick* The rocket is facing the opposite direction to that of its motion when a kick is given. This is a necessary strategy for the *Newton Corner(2)* or Newtonian strategies. In TARGET, the strategy is more specific in that the rocket would be brought to rest. This has to be borne in mind for later discussion. The strict version of *Antikick* is far more likely to occur in TARGET since the student has to initiate the motion which may be more likely to suggest the idea of stopping the DYNATURTLE before aiming.

- *Early* The rocket is moving to one side of the target but it is pointing to the other side. It is going to miss but the attempt was not too far out. This can be seen as a plausible try.

The assessment as to whether the rocket is stationary, aiming at the target etc are all subject to a small tolerance which is based on plausible level of accuracy on behalf of the user. An example is that the rocket is judged to be pointing perpendicular to its path if the appropriate angle is between 86 and 94 degrees.

Not all strategies were detected automatically. DiSessa describes three others of which one is irrelevant and the other two require looking at a fair number of the user's actions. The irrelevant one was named *Aim and Shoot* and seems to have only applied to the situation where the DYNATURTLE is initially at rest. Another, *Late implies Harder* requires that a kick resulted in a path which did not turn the DYNATURTLE enough...so, kick again. The final one, *Trajectory*, requires several kicks in a row with turns interspersed. This sequence was not often found by diSessa. It should not be too difficult to implement some automatic detection mechanism for these two strategies that would perform about as well as a human.

3.4 Observations on ROCKET Users

3.4.1 The Experimental Setup

ROCKET was integrated into the ongoing research project described briefly in section 3.2.2[7]. which involved, inter alia, trialing programs in a school classroom for a normal timetabled class of 'O' grade Engineering Science students. The consequence of these arrangements included the necessity of pairing the S5 students so that results must be interpreted in the light of this.

The package of ROCKET, Teacher's Notes, Student's Notes and Worksheets was pretrialed with a group of S3 students at Airdrie Academy, Hamilton. As a result, the program and worksheets were reworked and two observational sessions arranged in the same school: one with S4 students and the other with S5 students.

3.4.2 The Observations

Data was collected by means of storing dribble files, passive observation and filled in worksheets. On the whole, the dribble files were of the greatest interest.

Results from the S4 Pupils

There were five individual students all of whom tried both phases even though two of them did not follow the worksheets for the programming phase. Each person spent one and a half hours with the program and received the minimum

[7]Learning Engineering Science in School by Computer —see [Howe 83].

of help from the observers. Their work was assessed in terms of the number of occurrences of various strategies[8]. What follows is a brief overview of the results.

Aristotle Corner(1):

The Interactive Phase: Only 4 occasions in 163 games.

The Programming Phase: Only one occasion from a student working through the worksheets at the time.

Aristotle Corner(2):

The Interactive Phase: 96 occasions in 163 games.

The Programming Phase: 8 occasions in 68 games.

The usage of the strategies labeled here as *Aristotle Corner(1)* and *Aristotle Corner(2)* indicates that these students did not naturally adopt the strategy of turning the rocket until it was at right angles to the path although some students were inclined to use the right angle when using the *Early* strategy. *Aristotle Corner(2)*, however, proved a popular strategy which was used time and time again. The strategy of diSessa's of the same name was not seen but a variant was observed several times. This variant is, roughly, "aim at the target and kick, kick, kick" (figure 3–1).

Antikick:

The Interactive Phase: No occasions at all.

The Programming Phase: 6 occasions all in connection with working through various problems on the worksheets.

Inevitably, with their failure to utilise this strategy to bring the rocket to rest, there were no occasions of *Newton Corner(1)* or *Newton Corner(2)* at all

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[8]Frequently, students were observed to use various different strategies while playing a single game.

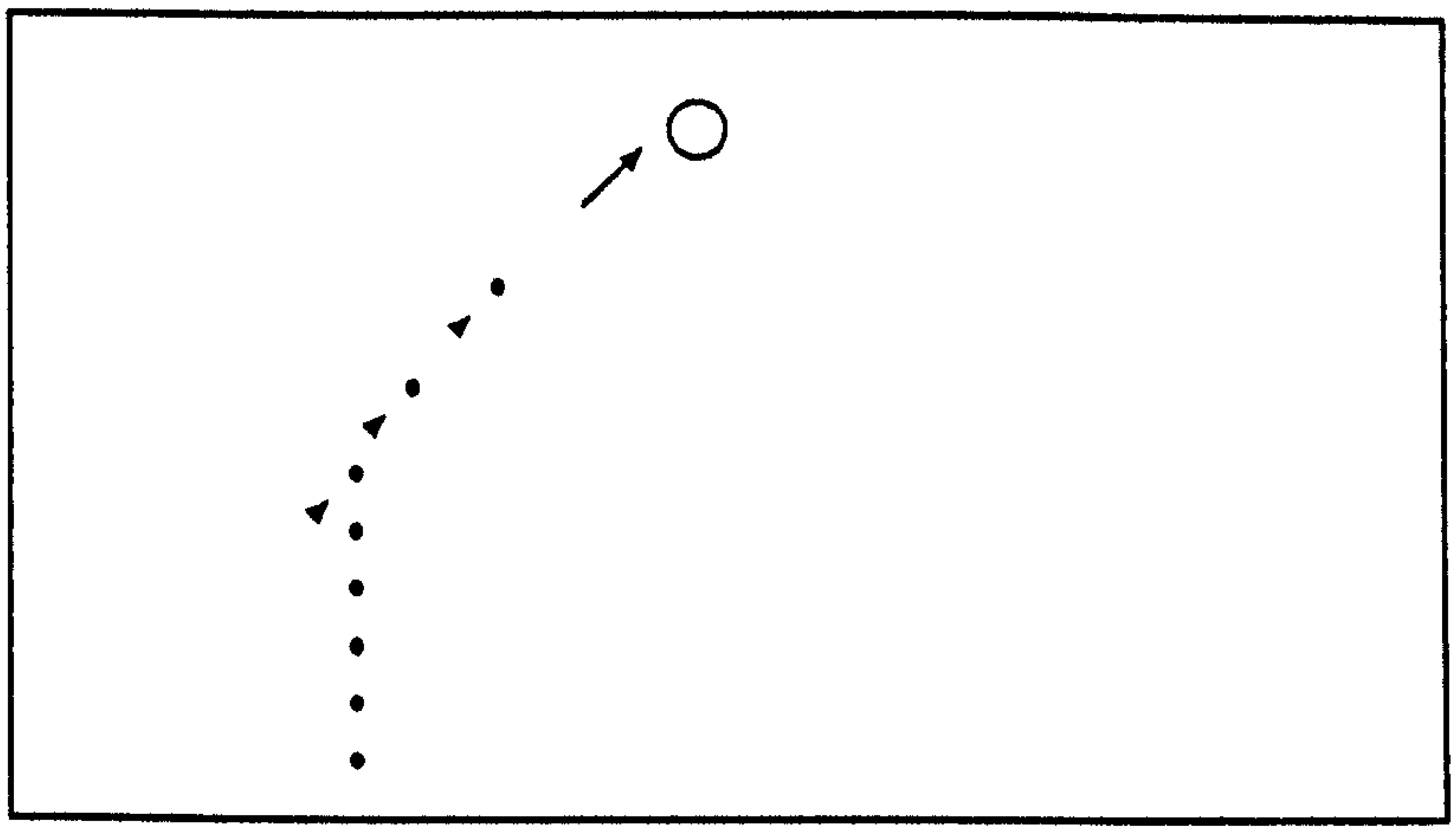

Figure 3–1: Keep on Kicking

in the interactive phase. Nor were there any instances of these strategies in the programming section.

Early Strategy:

The Interactive Phase: 139 occasions in 163 games.

The Programming Phase: 23 occasions in 68 games.

This more *Newtonian* strategy was used more frequently in both sections — see table 3–1. It is interesting to note that, in relation to *Aristotle Corner(2)*, its share went up for the programming phase which suggests that the *Early* Strategy might have been seen as more efficient by the time the students began the programming phase. On the other hand, determining that you are in a position to use *Aristotle Corner(2)* usually requires feedback which is absent in the programming phase.

Results from the S5 Pupils

There were four pairs of students all of whom tried both phases. Each pair worked with the program for one and a half hours and received the minimum of assistance from the observers. All of them followed the worksheets at some point

	% Interactive applications per game (I)	% Programming applications per game (P)	Drop in Use between Phases as a Fraction (P/I)
Aristotle Corner(2)	58.9	11.8	0.20
Early	85.3	33.8	0.40

Table 3–1: Early vs Aristotle Corner(2) for S4

but they did not do so very systematically. What follows is a brief overview of the results.

Aristotle Corner(1):

The Interactive Phase: No occasions in 77 games.

The Programming Phase: Five occasions in 101 games.

Aristotle Corner(2):

The Interactive Phase: 61 occasions in 77 games.

The Programming Phase: 10 occasions in 101 games.

Again, there is little evidence that the students thought of turning the rocket to a position perpendicular to the path. One can also see a more distinctive drop in the usage of *Aristotle Corner(2)* when passing from one stage to the other.

Antikick:

The Interactive Phase: 12 occasions in 77 games all of which were produced by one pair.

The Programming Phase: 25 occasions of which some were in connection with working through various problems on the worksheets. Only one pair failed to make a noticeable use of this strategy.

If there were no instances of this strategy then there were no occasions of *Newton Corner(1)* or *Newton Corner(2)* at all in the interactive phase. The one pair, however, made extensive use of this strategy.

Early Strategy:

The Interactive Phase: 47 occasions in 77 games.

The Programming Phase: 18 occasions in 101 games.

Again, *Early*'s share relative to *Aristotle Corner(2)* went up for the programming phase which suggests that the *Early* Strategy was seen as more efficient by the time the students began the programming phase (figure 3–2).

	% Interactive applications per game (I)	% Programming applications per game (P)	Drop in Use between Phases as a Fraction (P/I)
Aristotle Corner(2)	79.2	9.9	0.12
Early	85.3	33.8	0.29

Table 3–2: Early vs Aristotle Corner(2) for S5

Newton Corner(1):

The Interactive Phase: 1 occasion in 77 games.

The Programming Phase: 9 occasions in 101 games.

Newton Corner(2):

The Interactive Phase: 3 occasions in 77 games.

The Programming Phase: 2 occasions in 101 games.

Both these strategies were more in evidence with these older pupils.

A Case Study

The aim of this section is to look at the work of one particular pair of S5 students who made some use of the *Antikick* strategy. The pair chosen played some 22 games in the immediate mode and 20 games in the programming mode. We are going to concentrate our attention on the games played interactively. The analysis presented is not a detailed one as it is the intention to obtain some clues about their usage of very general strategies.

The Games Themselves The following table is an overview of the usage of four particular strategies that emerged from an analysis of the twenty two games. For any game, the column of numbers indicates the sequence in which the strategies were used —the top number being the first strategy used. The code used follows:

1. Aiming directly at the target while the rocket is moving at an angle to the target —the *Aristotle Corner(2)* strategy

2. Using a series of turns and kicks which produces rocket motion in a rough arc —roughly, the *Trajectory* strategy described by diSessa

3. Using the *Early* strategy followed by a simple debug

4. Using the *Antikick* strategy —mainly to reduce the speed of the rocket to zero

The row in table 3–3 headed *Hit?* indicates whether the student was successful in hitting the target while the row headed *2?* indicates whether the student appeared to be using the strategy numbered 2 above. As this latter judgement is quite a difficult one, only those examples which would appear to be deliberate have been included. Thus some games which seem to exhibit the strategy have not been included in the list because the strategy seemed to be the result of a frantic attempt to avoid sliding off the screen.

	Game Number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Hit?	n	y	n	y	n	y	n	n	n	y	y	y	y	y	y	y	y	n	y	y	n	n
2?	n	y	n	y	n	y	n	n	n	n	n	n	n	n	y	n	n	y	y	n	y	n
		3		1		3	1	1		4	4	4	4	4	3	3	3	3	3	3	3	
				3			1	1		1		4	4	4	1		1	3	3	1	3	
							1	1				4	4		3		3		3	4	3	
							1						4								3	
							1														3	
																					1	

Table 3–3: 22 Games of ROCKET

The first game (figure 3–2) to be discussed is their sixteenth game which illustrates one of the most successful strategies developed by students playing the game. It has been transcribed into the notation used in the programming mode and it is also annotated.

The game can be seen as a nearly successful attempt followed by a single

Wait	1	
Right	8	Aim more or less at the target
Kick	5	—essentially the *Early* strategy.
Wait	2	Wait to see the result.
Right	6	The kick did not bring the rocket
Wait	2	round enough so turn and try again.
Kick	4	Success this time.

Figure 3–2: GAME 16

successful debug. Variations of the above can be seen in games numbered 2, 4, 6 and 15-21.

The next game (in figure 3–3) is number 4 and it illustrates the attempted use of the *Aristotle Corner(2)* strategy. This crops up in games numbered 4, 7, 8, 10, 15, 17, 20 and 21. In many cases it can be regarded as a desperate attempt to do something before the opportunity passes. It is only in games numbered 4, 7 and 8 that the strategy is used as the opening attempt to hit the target. If this is compared with the nine opening uses of the *Early* strategy it is reasonable to assume that the student realised that aiming directly at the target is not too successful an approach.

Wait	3	
Right	2	
Wait	6	
Right	4	
Kick	4	Kick while aiming at the target
Wait	1	—ie *Aristotle Corner(2)* strategy.
Right	3	
Wait	3	
Right	8	Try to turn fast enough
Kick	5	to correct.
Right	1	
Kick	5	And again..but not successfully.
Right	2	
Kick	5	And again.
Right	2	
Kick	5	Success this time.
...		

Figure 3–3: GAME 4

Game four is a typical example of the strategy that diSessa refers to as *Trajectory*. It appears fairly frequently in one form or another.

The next game for consideration, figure 3–4, is numbered 11. It illustrates the explicit use of the *Antikick* strategy.

The pauses can be interpreted as due to a slight sense of uncertainty but there can be no doubt about the use of the *Antikick* strategy. It also happens that the above game is more properly an illustration of the *Newton Corner(1)* strategy but it is far more difficult to see the student deliberately choosing to perform this strategy rather than the similar *Newton Corner(2)* one.

Wait	4	
Right	10	
Wait	1	
Right	2	
Wait	1	
Right	6	Eventually face the opposite
Kick	4	direction to motion and kick
Wait	8	enough to bring the rocket to
Left	1	rest.
Wait	1	
Left	8	
Wait	4	Turn to face the target which
Kick	9	is at right angles to the
		previous path and kick.

Figure 3–4: GAME 11

It is worth noting that games 12 and 13 are determined attempts to produce an almost square orbit before trying to hit the target.

The last game to be considered, figure 3–5, is number 15 which contains a fairly clear example of the idea that the rocket's direction should be changed by a sequence of small kicks. Again, this is close to the *Trajectory* strategy of diSessa's. Both games 19 and 21 are similar. Unfortunately, in game 15, the student has overcorrected which leads to complications later.

Conclusion of the Case Study The four games illustrated contain some of the most widely used approaches found within the work of this particular pair of students. If one looks for a pattern to their work then one can see some signs of one: early games use the *Early* strategy in one form or another. The *Aristotle Corner(2)* strategy is used primarily in games 7, 8 and 9 and then *Antikick* is the main strategy in games numbered 10 to 14 inclusive. For some reason, the

Wait	2	
Right	10	Try *Early* strategy
Kick	1	but gently
Right	1	
Kick	1	Very small reapplications
Kick	1	
Kick	1	
Kick	1	
Kick	1	
Kick	1	
Wait	3	
Left	21	
...		

Figure 3–5: GAME 15

very successful *Antikick* strategy is then almost completely dropped and the pair essentially return to the *Early* strategy for the remainder of their games. The most likely reason for such a departure is that *Antikick* takes so long that it becomes a little tedious.

3.5 Conclusions

3.5.1 Summary of Classroom Observations

The older students were quicker at seeing the advantages of the more 'correct' strategies. They spent less time in the interactive phase than the S4 students. The idea of bringing the rocket to rest was generally neglected as most student seemed content to utilise *Aristotle Corner(2)* and *Early*. Generally speaking, it would seem that the students moved from using *Aristotle Corner(2)* to *Early*

Strategy. Some evidence about their methods of problem solving could be extracted from the data but no attempt will be made here.

There is also evidence that they spent very little time on the worksheets. What results there are indicate some small confusions. For example, in describing the effect of the *Right* command, one student declared that:

> The rocket turns to the right but still rises to the top of the screen

He wrote something very similar for the *Left* command and then, for a series of *Kick* and *Right* commands:

> The rocket turns to the right

There is one other example from the limited data available that indicates potential confusion between a rocket turning left (anticlockwise) and a rocket moving to the left (having a horizontal component).

There are some indications that they did not read the description about the way to 'program' the rocket in that several people did not use the *Wait* command.

3.5.2 Reflections on diSessa's Learning Path Chart

The *Learning Path* chart produced by diSessa is a somewhat more complex chart than could be produced by a careful analysis of the results obtained through the use of ROCKET. For example, it is very difficult to see how to tell that a student is using the advanced *Control Velocity* strategy without knowing what the student believes what they are trying to do. In many situations, the gross physical consequences will be very similar to a *Compromise* strategy. There is worse to follow: a student who has mastered the whole set of strategies and beliefs that relate to the chart may still make use of any aspect —even if the strategies used were the *Aristotelian* ones. A knowledgeable student may still make use of strategies that do not result in the rocket going towards the target in order to gain a positional advantage. The strength of the chart is quite clearly to indicate something of the path that a *Newtonian novice* might take in order to become an expert. The indications are that using ROCKET to try and hit the target does not guarantee that any observer —whether this is a teacher or a computer— can tell when mastery of the chart's subject has been achieved.

The important question is whether the students can learn physics by this means in the normal classroom context. White has shown that there is evidence that learning does take place provided that a more structured approach is taken. Her series of eleven games is an interesting attempt to flatten the *Learning Path* chart into a more linear sequence. Unfortunately, her original sequence of games has to be reordered in the light of her results. Nevertheless, even as part of a sequence of games, the utility of such a program as ROCKET is in question.

3.5.3 Why Modelling Might Prove More Useful

It was accepted at the beginning of the work on ROCKET that the modelling dimension was absent. The promising aspects included the stress on 'playing' with misconceptions and the work done to produce an explanation of how the skills required are related to a developing Newtonian understanding of dynamics.

Misconceptions

There are a number of misconceptions that have been reported in the research literature that ROCKET (or TARGET) could not easily uncover, notably, those associated with the presence (or absence) of a continuous force. The next chapter amplifies the concern for covering a wider set of problems with a single environment.

Language and a Model of the Student

Can a model of the student be inferred with the help of ROCKET? The programming language used in ROCKET shows little of the conceptual structure by means of which the student decides to do one thing rather than another. The language by means of which the student communicates with the computer is too close to the phenomenological level to easily abstract the interesting information about how the student perceives the problem. A modelling language would be an advantage here: if students had to implement their own strategies using a high-level language then the situation would be more useful. In computational terms, the language might be LOGO or Smalltalk-80 but the type of high-level language needed to write strategies for ROCKET requires a set of primitive operations that reflect the cognitive skills discussed above.

For example, with the primitives in figure 3–6 and a few control primitives it would be possible for students to write their own simple programs to hit the target. The names of the above predicates suggest their semantics. It might

Commands

fire_motor(amount)	turn_left
turn_beyond(amount)	turn_right

Predicates

pointing_at_target?	dithering?
straddling_target?	stopped?
aiming_to_left?	going_to_left?
aiming_to_right?	going_to_right?
pointing_at_right_angles_to_path?	pointing_back_along_path?

Figure 3–6: New Primitives Suggested for ROCKET

also be sensible to provide functional versions of several of these predicates that return useful values. The implications of this suggestion will not be followed up here.

Figure 3–7 is a plausible attempt to code the *Aristotle Corner* strategy. Given a language with concurrency such as the one described by Chung and given that he reports some success in getting S4/S5 students to use concurrent programming concepts such as guards it would be interesting to take this further [Chung 86]. Of course, it might turn out to be too difficult a task or too expensive in terms of time.

```
trying_to_point_at_target by
        while aiming_to_left
                keepon turn_right
        while aiming_to_right
                keepon turn_left
end

hit_target by
        while not pointing_at_target
                keepon trying_to point_at_target
                then fire_motor
end
```

Figure 3–7: A Version of Aristotle Corner

The conclusion is that the current language used for ROCKET is too closely equivalent to *machine code* to be useful. The next chapter, however, outlines a different approach from the one sketched out above.

In the Classroom

There are a number of advocates for the *microworlds*[9] approach including Papert [Papert 80] but they must be flexible enough to provide several modes of use in the crowded classrooms of our schools.

ROCKET provides a reasonable degree of such flexibility. For example, one mode of use for ROCKET is a cooperation between the teacher and his/her

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[9]The term *microworlds* has been badly abused in recent years. Here, the meaning is that a microworld offers a reasonably self contained but simplified representation of some aspect of the real world. This still leaves the concept somewhat underspecified but, using the definition, ROCKET, DYNLAB and ELAB are all microworlds.

students in their combined use of the system where the rôle of the teacher is to detect the problems that the student is facing. The extraction of the right kind of information by the class teacher depends on a number of things including the training that the teacher has had on the *educational* use of the program and its ancillary materials.

Useful information can be obtained by three or four methods. The teacher can engage the student in a long conversation to encourage the student to discover the nature of his/her own difficulties and to spot suitable moments for intervention. This is in imitation of the research orientated approach used by diSessa. An alternative is to rely upon the program ROCKET to output useful information on the state of affairs pertaining to each *interesting* moment detected. The current version of ROCKET taken together with the ability to playback sessions is too cumbersome but can be quickly improved given a machine of greater power than the APPLE II plus originally used. The final option might be: if the teacher is too busy to spend a great amount of time quietly sitting or too busy at the end of lessons to get the data from the machine and play back some of the interesting sessions why not rely on the teacher's abilities to detect various strategies from a quick glance at the screen?

This opens up an interesting line of thought: can the informed person reliably tell what strategy is being used from a snapshot of the rocket's path? Figure 3–8 illustrates four snapshots. The four games in this figure are the output from a simple student simulator playing ROCKET.

Each game represents the results of applying a different strategy. The top right game represents a strategy based on a heuristic that the rocket is turned until the target is straddled by the direction in which the rocket is pointing and the direction of motion. The rocket is *kicked* according to a reasonable compromise. The other three games represent different versions of the *Aristotle Corner* strategy. See appendix C for more details about the various strategies examined.

It is worth commenting on the bottom two games which are identical. The bottom left game represents a student who uses either *Aristotle Corner(1)* or

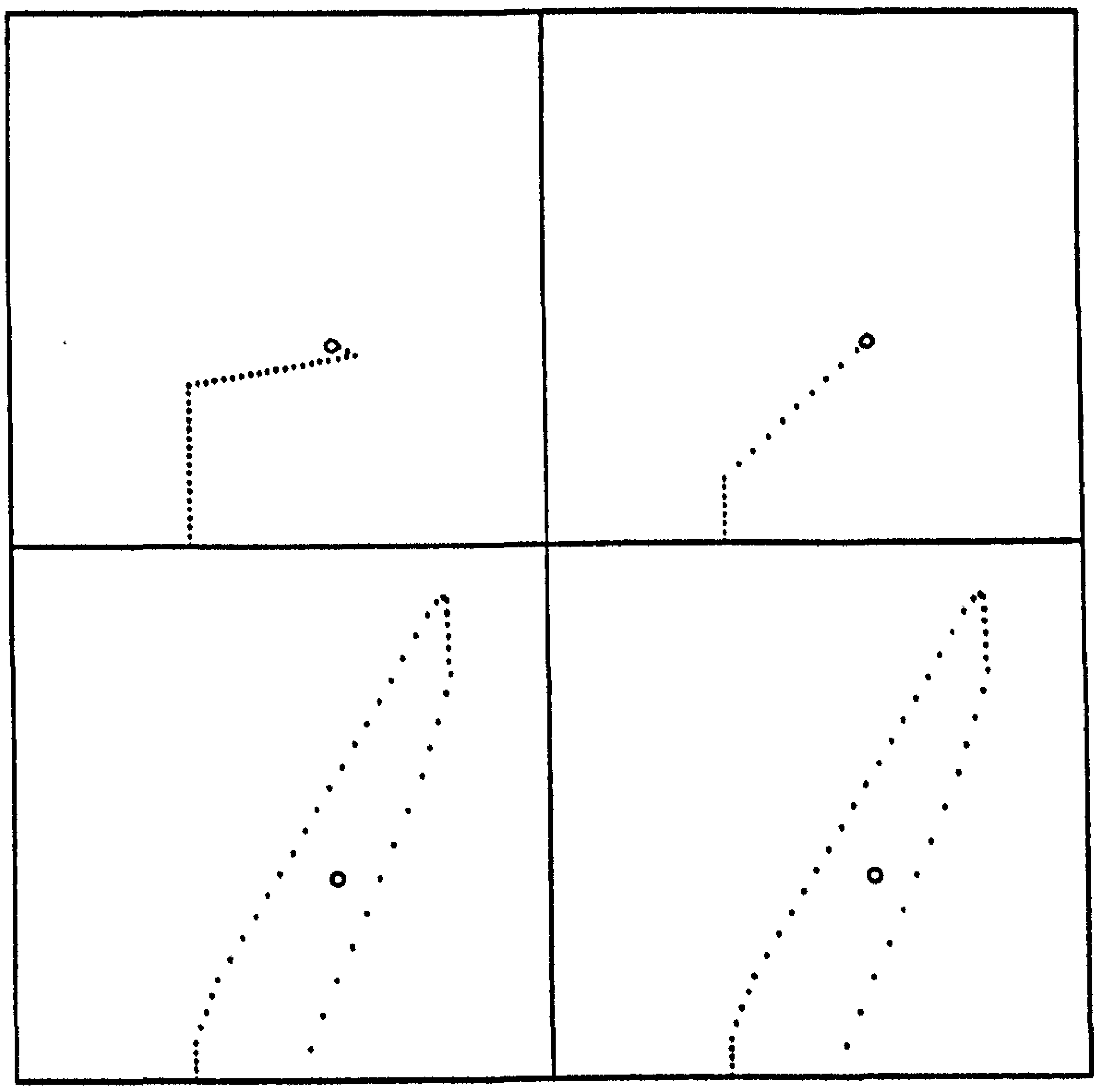

Figure 3–8: Four Example Games

Aristotle Corner(2) as appropriate. The bottom right game represents a more sophisticated strategy which only uses *Aristotle Corner(1)*. This result suggest two things. First, if two strategies based on different physics misconceptions were to lead to indistinguishable behaviour then the value of ROCKET would be diminished. It would be hard to say that the two identical games provide evidence to support this possibility. Second, the teacher is hard pushed to identify the specific strategy actually being used. An automated assistant would be useful but it would have to observe a series of games in order to make the necessary distinction between the identical games illustrated above.

In practical terms, therefore, it would be necessary to supplement the teacher's own insights with the program's own information. For example, part of the analysis above was achieved with the help of the program's attempt at the automatic detection of significant events although the criteria for detection are quite crude and have not been highly tuned. Yet the analyser yields results which seem highly compatible with the performance of at least one human (the author). Indeed, an attempt could be made to add a so-called *Intelligent Tutoring System* to handle the kinds of intervention that diSessa describes but this approach will not be pursued.

3.6 Summary

ROCKET provides a simple yet revealing simulation environment in which students have been shown to demonstrate non-Newtonian concepts. It might be argued that simulation environments provide sufficient facilities to help students re-evaluate their beliefs in the light of their experimentation. The evidence gathered here does not support this.

Students do not follow the *Learning Path* described by diSessa. The *Learning Path* therefore has to be interpreted as prescriptive rather than a description of the learning that takes place (in some normative sense). Further, it cannot easily be inferred from the students' behaviour that they have confronted some non-Newtonian misconception and overcome it. They can evade the issue in a number of ways and they can utilise 'non-Newtonian' tactics as part of their overall strategy even when they do not have misconceptions.

ROCKET was provided with a means of automatically identifying strategies and this proved useful. Detecting that learning has taken place often depends crucially on the evidence gathered over more than one game. If such environments are to be used in a classroom situation then the teacher needs an automatic strategy detection facility in order to obtain assistance with the diagnosis of students' misconceptions.

The use of ROCKET has some advantages over TARGET. The simple LOGO-like programming language provided by ROCKET forced the students to do more planning. Even though this language was very restricted it gave students the necessary opportunity to speculate on what might happen as a consequence of their actions. The situation can be further improved by the provision of a programming language that better reflects the fundamental structure of the beliefs that students hold.

It is important to consider how effectively the student learns dynamics within the context of some microworld. It is therefore necessary to create a more powerful environment than that of ROCKET. The next chapter details a program which can be seen as an extension of ROCKET.

Chapter 4

Modellable Misconceptions in the Dynamics Domain

4.1 Misconceptions and Dynamics

What are the common misconceptions found within the domain of dynamics? In the previous chapter, the main contributions of diSessa and White have been outlined. There are, however, a number of other studies that must be taken into account.

4.1.1 Kinematics

A large number of studies have been made in the subdomain of kinematics which have a bearing on the problems that students have with dynamics. These include important work by Trowbridge and McDermott who identified a number of problems with both velocity and acceleration [Trowbridge & McDermott 80, Trowbridge & McDermott 81]. Common problems include:

- Identification of equal speed with the place where one object passes another when they are both going in the same direction.
- One object being ahead of another travelling in the same path meant that it was travelling faster.
- Various confusions of position with acceleration.

- Various confusions of velocity with acceleration.

Other work by Raven and Rae is relevant [Raven 72, Rae et al 77]. Work by Ehri and Muzio indicated problems that students had with angular velocity [Ehri & Muzio 74] while work by Saltiel investigated different frames of reference [Saltiel & Malgrange 80].

4.1.2 Dynamics

Some important work on momentum has been done by Raven who indicates that, despite a *Piagetian* analysis which suggests that the concept of momentum is more difficult than that of either mass or velocity, children were able to cope with the concept in an informal and 'global' manner [Raven 68]. This is by no means the only work that supports the idea of using such *compound concepts* before teaching the prior ones. Robertson and Richardson indicate that students can attain conservation of some concept before that of some constituent concept [Robertson & Richardson 75] and Wilkening indicates that young children can handle certain judgements about velocity before ones about time [Wilkening 81].

Further, Williams detected a number of misconceptions about momentum with pre-'O' level students [Williams 76]. He notes, inter alia:

- A failure to distinguish between vector and scalar quantities.

- Newton's third law is misunderstood in that, in an interaction, the larger object is given the larger force. A further problem is that the third law may only be seen to apply if one of the bodies is at rest.

- A belief that, for a perfectly elastic collision of a body with a wall perpendicular to its path, there will be no force on the wall.

Maloney reveals a deeper set of misconceptions associated with Newton's Third law [Maloney 84]. He demonstrates results classified in terms of three contexts and two forms of the deductions made about two interacting bodies. The forms of misconception that he analyses are that the body with the greater mass applies the greater force and that the 'causative' agent applies the greater force.

Work by Shannon indicated that college students held non-Newtonian views on a simple task [Shannon 76] while Leboutet-Barrell indicated the widespread problems that students have with dynamics [Leboutet-Barrell 76] which seems to indicate that there are two kinds of force: a force of interaction and a force due to motion. Further, there is evidence that motion is seen as an intrinsic property of a body in much the same way as its mass. Viennot's work has been particularly important in the analysis of the various conceptions of force that students possess [Viennot 79].

Both Clement and Champagne have produced evidence of non-Newtonian beliefs about Dynamics [Clement 82, Champagne et al 80]. Clement's experimental results indicate a widespread belief that motion implies a force. This particularly showed up the situation in figure 4–1. The rocket motor is switched

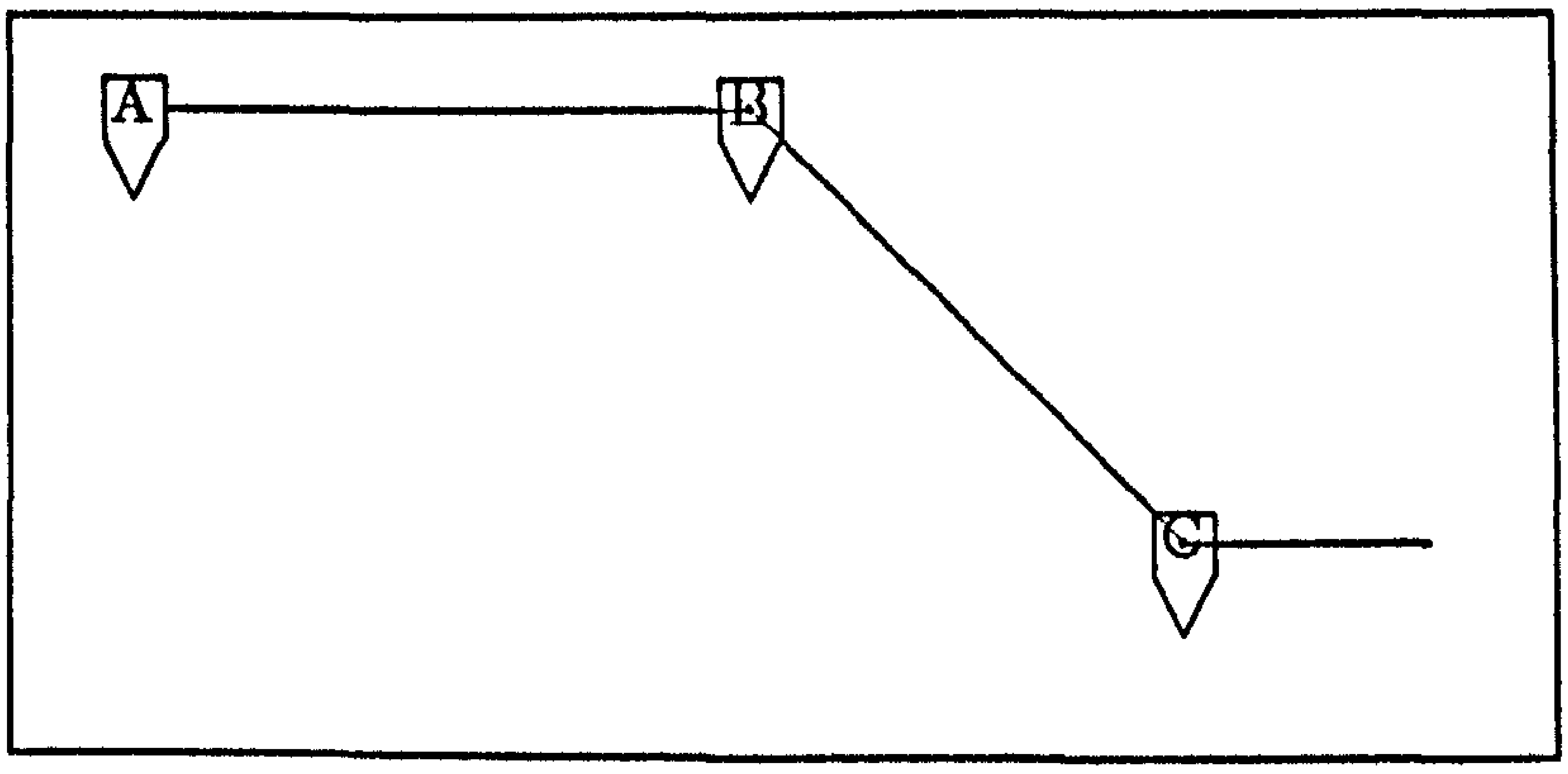

Figure 4–1: Motion implies Force!

on briefly at B at right angles to the path from A to B. Some students believe that the rocket's direction returns to its original value after a while.

Champagne has also found evidence that some students believe that a dropped object instantaneously reaches a maximum velocity and then falls at constant speed, heavier objects fall faster than light ones (et cetera paribus) and that closer to the earth means heavier. Further work by McCloskey, Caramazza and

Green indicates Impetus theory-like beliefs about the paths taken by objects once some constraint that causes the object to follow a non-linear path is removed [Franklin 79, McCloskey et al 80, McCloskey 83, Caramazza et al 81].

Warren makes numerous observations about the teaching of the concept of force [Warren 79] and Ogborn has taken ideas from Hayes and diSessa to elaborate an account of how students develop misconceptions in the domain of dynamics [Ogborn 85, diSessa 82, Hayes 79].

4.2 More Difficulties with Dynamics

Other major themes have been identified as posing problems for students: vectors [White 81] and the drawing and interpretation of speed-time graphs [Preece 82, Avons et al 81b, Avons et al 81a]. White focusses on both aspects of vector representation and on the inherent problems associated with analogies between vector and scalar addition. There are other difficulties.

4.2.1 Distance and Displacement

An analysis of the problems that students (of Engineering Science) were likely to have with topics in Dynamics using the standard recommended textbook reveals a number of problems [Brna 83, McCorkindale 80]. Confusion of the distinction between distance and displacement through the use of identical symbols, confusion over the status of displacement as a vector quantity, lack of reinforcement of the distinction both in terms of examples and set problems, lack of stress on the direction of any displacement mentioned, lack of distinction between distance-time and displacement-time graphs, no opportunities to reinforce the distinction by means of set problems and the curious problem of *negative displacements.*

4.2.2 Speed and Velocity

In the same book there are further problems with the definition(s) of speed, confusion of the symbols for speed and velocity, confusions between instantaneous and average measurements, few problems to reinforce the idea of average velocity, lack of distinction between (magnitude of) velocity-time and speed-time graphs and problems in making explicit the connections between positive and negative displacements and velocities.

4.2.3 Acceleration

There are further confusions in the definition of acceleration which is defined as the change in speed over time and continuing difficulties about signed directions and signed accelerations. Without indicating a choice as to which direction is taken to be positive it is declared[1] that:

> For bodies thrown upwards away from the centre of the earth, their speed will decrease because of gravity and therefore g is a negative acceleration in this case (i.e. a retardation or deceleration).

Unfortunately, there is an alternative explanation. It seems that the one quoted is the more natural —but why? Those familiar with such problems tend to take their choice of a positive direction from verbal cues in the problem statement. In this case, the phrase "thrown upwards" indicates upward as the positive direction but why should it be assumed that students who are learning the subject will instinctively pick up the same cue?

Another example:

> For bodies falling toward the earth, the speed will increase, therefore g is a positive acceleration.

---

[1]See page 18 in [McCorkindale 80].

Combined with the previous situation, the evidence for verbal cues becomes stronger —but so does the potential confusion of the student unless s/he is made aware of these issues in an explicit way.

In particular, the above may throw some light on the results of one of the experiments of Trowbridge and McDermott [Trowbridge & McDermott 81]. Their experiment involved rolling a ball along the line of greatest slope up a plane and then allowing it to fall back. Many students, when asked for the acceleration of the ball at the top of its motion, replied that the ball had zero acceleration. Going by the above method for determining the direction to be taken as positive, consider the following situation:

> A ball is thrown upward. It eventually returns to the thrower. What was the acceleration of the ball at the point where it was at its greatest height?

The solution might run something like this:

> Since the ball is thrown upward, the positive direction is up. The speed will decrease because of gravity. Therefore the acceleration is negative. On the way down, the positive direction is down. The speed will increase because of gravity. Therefore the acceleration is positive. Just before the ball reaches its greatest height its acceleration is negative. Just afterwards, its acceleration is positive. At its greatest height it can be thought of as both going up and going down. Therefore, it has to have an acceleration that is both positive and negative. Therefore, at its greatest height it has an acceleration of zero.

This is only one possible explanation as to how a student might draw the conclusion that the acceleration is zero at the point where the body is momentarily at rest.

In view of the tendency of students to confuse velocity with acceleration [Rae et al 77], it might be worth mentioning that the argument works with few alterations if the word *acceleration* is replaced by *velocity*.

The argument is correct for velocity because the numerical value of the velocity is vanishingly small as the body nears the greatest height position which means that the 'discontinuity' that arises as a consequence of altering the way we measure quantities has no effect on the continuity of the velocity. The acceleration, on the other hand, is made discontinuous. Since physical quantities are usually regarded as varying continuously it would be quite reasonable for a student to dislike the idea that the acceleration makes a large *jump.*

If it is now assumed that the student knows that, even up till a millisecond before the greatest height, the acceleration is numerically -9.8 and that just afterward it is +9.8 then the student may prefer to believe that the acceleration passed through all the intermediate values and through 0 at the greatest height position (by a symmetry argument) rather than call into question the effect of his definition of the positive direction.

It seems more likely that a student taught to define positive in terms of verbal cues —who may not even be aware that s/he is using verbal cues— might have greater difficulty in obtaining a correct answer to the above problem than one who was taught to be more aware of the effects of changing the way things are measured. Whatever is really the case, the results of a similar experiment by Trowbridge and McDermott [Trowbridge & McDermott 81] indicate that a fair percentage of college students will give the answer of zero!

4.2.4 Force, Mass and Gravity

There is a definition of force as *that which causes or tends to cause motion.* This is seriously wrong. Consider the status of friction: in the Newtonian formulation, friction is a force but it is difficult to see friction causing (or tending to cause) motion.

If the definition is not Newtonian what is it? The answer is that it is nearly Aristotelian and, historically, Aristotle's views on dynamics were the ones that were dominant prior to the work of such people as Galileo and Newton. For motion to take place, whether it be constant velocity or not, something akin to a force had to be applied. If a body were at rest, then a force had to be applied to cause motion. If a body were in motion then a force would need to be applied to maintain the motion. Thus one could say that force was causally responsible for motion. Newton altered this view so that *force* became causally responsible for a change in the velocity of the body.

Thus such a definition of force has a non-Newtonian flavour. It is nearer in spirit to the Aristotelian view. Now, it may be believed that the learning path [Gagné 77] of the student must attain the Newtonian point of view by first introducing the Aristotelian view but there is no indication that this approach is intended. Indeed, it is difficult to avoid the feeling that students holding such views are not going to be able to formulate a coherent view of Newton's Laws.

4.2.5 Vectors

If the student cannot participate in situations where direction has assumed some importance then it is unlikely that the concept of a vector will be as useful as it ought to be. As it is common to meet the one dimensional world first it is unlikely that the student will be able to gain the degree of familiarity with the need for the specification of direction. After all, the 'direction' in one dimension is wrapped up in the sign of some quantity —it just drops out with the ordinary arithmetic. This scarcely demonstrates the degree of complexity that vector addition possesses when performed in two or three dimensions.

It is also difficult to avoid some artificiality in the statement of one dimensional problems that request vector rather than scalar treatment. Not so with two dimensional problems. To place the student in an environment within which two dimensional vector quantities are the natural entities to manipulate must be an advantage. Having 'played' around with 2D vectors for a while, the student will have built up enough cognitive structure on the subject to enable her/him to go on to the 1D case and to appreciate the need for + and - signs etc.

The problem with such an approach has always been the need for the student to handle some quite difficult arithmetic. Champagne et al have found some evidence that mathematical ability can be a good indicator as to whether a student is going to learn mechanics well or not. Their explanation is that the student who can handle the mathematics can concentrate on the physics [Champagne et al 80]. This suggests that if ways could be found to uncover the physics of vector quantities without the need to cope with the mathematics then the 'average' student with mathematical difficulties might be placed in a better position.

All the above suggests that some advantages flow from a qualitative two dimensional treatment of vector quantities. It is possible to design a world which removes the burden of arithmetical computations from the student thus enabling him to build up his understanding. For example, prior to using ROCKET, students had also used two other programs[2] (VECTOR and N1) which provided practice with the vector formalism of displacements and velocities respectively.

4.2.6 Graphs

For each of the topics of velocity and displacement there are problems when it comes to drawing graphs. Apart from problems of scales and interpretations there is a selection problem: for example, whether to choose a distance vs time or displacement vs time graph. Students ought to be able to determine which of these two graphs is appropriate for a given problem. For the moment, consider an example by means of which the student is introduced to distance-time graphs in McCorkindale's book:

> A cyclist noted that he travelled a distance of 5 metres every second while free wheeling down a hill. Draw the distance/time graph for the first 4 seconds of his freewheeling.

Consider the same question slightly altered:

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[2]Both these programs were designed and programmed by the author of this thesis as part of his contribution to the "Learning Engineering Science in School by Computer" project [Howe 83].

A cyclist noted that he travelled a distance of 5 metres every second while free wheeling down a hill. Draw the displacement/time graph for the first 4 seconds of his freewheeling.

Could both these questions be answered? The answer is yes, provided that the assumption of straight line motion is made for the second question in which case both graphs would look the same (except for the label on the y axis). What are the implications for the student? How is the relevant graph to be determined? It is quite likely that the student's understanding of the situation is overridden by the command to draw a certain type of graph. What would happen if it were up to the student to select the most appropriate graph? Would there be any confusion? If so, might it not be because there seems to be so little difference between distance and displacement in the presented context? It is quite possible that some of the confusion that arises in the mind of the student does so because two concepts are too close together within the context in which they are met. In the above case, one might illustrate the difference between displacement and distance with reference to two dimensions but actually apply the concepts to motion in a straight line in one direction only.

If insufficient emphasis is placed on the vector nature of displacement, the difference between a distance-time and a displacement-time graph is easily ignored. How is the student to learn the criteria to apply to the choice between a distance-time graph and a displacement-time graph? A common solution is for the teacher/book to make an explicit statement as to which is the correct graph. This evasion is highly suspect but difficult to avoid.

4.2.7 The Transition from Informal to Formal Explanations

There is a basic problem with explanations of force. The first attempt to introduce force as a concept is usually by means of an appeal to the informal usage of the word. This guidance is an attempt to provide a link (or links) into the existing relevant cognitive structures. One such structure is related to the student's naive notion of force. This notion is built up over a length of time far in excess of the time spent in the classroom considering the formal description of force. The physics teacher will often make an appeal to such notions which have been built up from such verbal descriptions as

He forced the lock

The police force

He forced the tomatoes

He forced his way into the room

and from various images such as the sensations caused by muscular activity, being pushed to the ground and numerous others. Analysis by Osborne and Gilbert [Osborne & Gilbert 80a, Osborne & Gilbert 80b] of students explaining instances and non-instances of the concept of force has exposed a variety of informal attitudes with implications that are difficult to ignore. In one such view, force is seen as a property of the body in much the same way as mass is predicated of a given body.

The links to this body of informal knowledge may seem easy to make but it would seem quite possible that some links are more valuable than others and even that some links are actually detrimental to the formalisation that is about to be taught. Thus it would seem that the teacher who appeals to some informal notion of force and then goes on to talk about forces in the formal context of Newtonian Dynamics cannot assume that the informal and the formal views can be kept in separate compartments by the student [Johnson 67]. After all, it is often the teacher that can be accused of confusing the issue.

After making the informal connections, an example might be cited. Typically, this might involve an appeal to the need to accelerate a body from rest to some speed over some period of time. This approach has an obvious weakness even if the consequences are less clear. For example, both the Newtonian and Aristotelian explanation might easily coincide when it comes to giving a qualitative account of the situation. Worse, if an appeal is made to feelings of muscular activity, the student will see that once the body is in motion it requires a steady but non-zero effort to keep it in motion. Thus the Aristotelian view might be reinforced, making the task of presenting the Newtonian view much harder.

This problem might be solved by not making an appeal to intuition but by placing the student within an environment where the difference between the two explanations becomes strongly biased in favour of Newton's interpretation. By this it is meant that the explanatory power of Newton's Laws is seen as greater than any other informal explanation that the student could muster.

One solution, already discussed, involves placing the student in a microworld in which friction is inoperative as it is friction that can be seen as the complicating factor. For, without friction, bodies would more easily be seen to move at constant velocity without the need for the application of a force.

Another problem occurs with the explanation of the effect of gravity. It is often stated that the earth pulls apples off trees etc. What is not stated so frequently is that the apple also pulls the earth toward it. To say it another way, the symmetry of Newtonian gravitation is not exploited [diSessa 77]. Presumably the reasoning is that the student can see the effect of the earth on the apple but cannot see the effect of the apple on the earth. In fact, the student cannot see the effect of the earth on the apple but can see the change of state of the apple and infer, hopefully, a Newtonian cause. If the student cannot see the change of state of the earth, why should it be necessary to infer a gravitational attraction of the apple on the earth?

The weakness of teaching the connection in an asymmetric way seems to lie in the introduction of a sort of privileged frame of reference. That the earth attracts things to it rather than things attracting the earth to them has a pre-Copernican flavour. One may wonder whether we are really teaching a coherent theory of gravitation to the student.

Again, it would be an advantage if the student could be presented with a world in which bodies of fairly similar mass were mutually attracted so that the symmetry of gravity could be perceived. Then an analysis of the observed behaviour of the earth and the apple might be a little more straightforward.

4.3 What Misconceptions might be Modelled?

Having identified a large number of misconceptions that have a bearing on the development of expert performance in dynamics, it is time to consider what classes of misconceptions are of interest. To make this clearer, there are two interesting questions: what *can* be modelled and what is *worth* modelling.

The latter question will be discussed in two parts: those situations for which DYNLAB, the modelling environment to be described in this chapter, can be used and those that require a much more complex environment. Not all the situations modellable with DYNLAB will be investigated as it proved necessary to be selective. First, however, it is worth having a brief look at a categorisation of misconceptions.

4.3.1 Descriptions of Classes of Misconceptions

Misconceptions can be of various kinds and a description of the various classes of misconception must inevitably depend on the view taken of the way in which knowledge is learned, stored and activated. The general view adopted is that knowledge is stored in a number of ways including facts, (informal) rules of inference and partially constructed plans. For each passive or active cognitive component there may be associated misconceptions. In a very general way, misconceptions may be attributed to incompleteness, redundancy or incorrectness[3]. This applies to both declarative and procedural forms of knowledge.

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[3] A misconception is a belief and not a failure of performance. An analysis of slips belongs elsewhere.

The person with a misconception may, for example, simply have a piece of factual information wrong. For example, a delusion that the normal value for the acceleration due to gravity is to be taken as $9.6m/s^2$ in normal school laboratory work[4]. This *may* have deeper ramifications but these are mostly of interest to a discussion about how such beliefs arise. Note that such an error can only be regarded as a misconception if it is believed that a concept is attached to a number of (possibly mental) procedures which can extract useful values associated with various aspects of the concept.

Here is a brief list of some of the possible classes of misconception:

- Interpreting Sense Data
  - Attributing the wrong temporal sequence to events
  - Attributing the wrong causal sequence to events
  - Attributing causality to the wrong agent
- Storing Information
  - Attaching the wrong name to a concept
  - Attaching the wrong value to some property of the concept
  - Possessing a faulty taxonomy of concepts
  - Possessing the wrong preconditions for learned procedures
- Processing Stored Information
  - Faulty syllogistic reasoning in certain contexts
  - Faulty qualitative reasoning in certain contexts
  - Propagating constraints wrongly
  - Possessing faulty decision procedures

[4]The common working values are $9.8m/s^2$ or $10m/s^2$.

The above permits some misconceptions to be described in more than one way. This is reasonable as the division of misconception descriptions depends on what perspectives on mental processes are adopted. If, for example, it is believed that syllogistic reasoning is not a fundamental attribute then there would be a natural reluctance to include misconceptions about syllogistic reasoning as a category. In this case, syllogistic reasoning would become a domain of knowledge much the same as Cooking or the study of Latin.

Some items in the list are arguable. Indeed the words *faulty* or *wrong* are used to describe misconceptions. These words are intended to indicate the sense that certain conceptions are different from the ones normally accepted by science teachers.

Some items in the list seem to reflect possible mental structurings. For example, if a student believes that force and energy are synonymous (possessing a faulty taxonomy of concepts) then it would be plausible if this were reflected in the stable cognitive structures of the student. If, on the other hand, a student cannot decide when two bodies travelling in the same direction are travelling with the same speed (possessing faulty decision procedures) then this might be a reflection of the absence of cognitive structure. If this is the case then it is believed that the student will generate a procedure to make the required judgement based on the student's current structures. Further misconceptions may come into play as an attempt is made to recover from an *impasse* (see [Brown & VanLehn 80]).

As a further example, Larkin has been interested in how students who are novices differ from experts in their attempts to solve simple kinematic problems [Larkin et al 80]. She identifies expert behaviour as akin to the execution of a plan whereas a novice, not having any plans to execute, has to reason in a means-ends manner[5]. Can a student who lacks the necessary plans be regarded as holding a misconception? Such a position would be unreasonable. If a student

[5] Which may, in turn, reveal misconceptions related to the category of faulty decision procedures.

possesses most, but not all, of a plan and believes this to be a complete plan then the student has a misconception. A student cook who knows a number of plans to prepare food for the oven but does not know anything about the rôle of ovens certainly has a misconception about the nature of cooking!

Not only are the various sources of misconceptions of interest to educators but how misconceptions manifest themselves. The sources of such problems may yield information which will help curriculum designers design courses to avoid fostering certain types of misconception or, more plausibly, confront the issues more directly (see, for example, [Driver 81, Soloman 83, Osborne et al 83, Zeitman & Hewson 86]). This latter option is the more sensible in that it is not possible to eradicate all misconceptions for any particular student in such a way that, thereafter, the student never generates any new misconceptions. Such an endeavour seems analogous to the medical program to make everyone perfectly well so that no one will ever be ill again. It seems vastly better to teach students how to debug their own faulty beliefs if such an enterprise can be carried out with some success. The problem is that there are pessimists who believe that the effort would be too great, the results marginally better at best and the effects not generalised by students in any useful way.

4.3.2 What Makes a Misconception Modellable

Consider the accessibility of some arbitrary misconception. The student may be able to verbalise this misconception quite clearly. Another student with the same misconception may not be able to describe it at all. It is tempting to suggest that the various procedures on which the problematic belief depend have been 'compiled' and can only be decompiled with great difficulty. The student in this state may be aware that there is a fundamental belief that is in doubt but may struggle to express anything that might look like a description of the problem. A third class of student gives all the signs of being entirely unaware of the assumption that is mistaken. Such students have compiled their knowledge into a procedural form to such an extent that they have no access to the assumptions upon which their actions are based. They may have simply learned the procedure, a form of instrumental learning criticised by Skemp and many others [Skemp 79].

The first level of accessibility for the student or teacher is an assessment of whether or not the phenomenological evidence fits expectations. If it does not then the student may look for some account of why there is evidence of some gross misbehaviour —on the part of nature or his/her reasoning process. If some evidence of the faulty flow of events can be found then the student may be able to go on to pinpoint the faulty belief(s) which underlie the surface evidence. This coarse description can be thought of as a description of how students debug their personal conceptual models.

The problem of accessibility is coupled to the question as to whether some faulty behaviour can in principle be associated with faulty beliefs. If it is known that there are situations in which student behaviour —linguistic or otherwise— manifests the symptoms of some underlying misconceptions then it is necessary to be confident that these mistaken beliefs can be described.

Further, if some modelling system is to be used successfully then the students themselves must have some chance of describing their own beliefs given a reasonable amount of time, good will and determination. For example, in the situation described by Larkin, novice students may have to reason from the *givens* in some problem to the *soughts* [Larkin et al 80]. These students may have mistaken beliefs about a number of things, including how this process of means-ends analysis proceeds. Asking a student to precisely describe the algorithm that they use would seem to require more of the students than they are likely to be capable of doing.

4.3.3 Modelling Using DYNLAB

The situations actually chosen for modelling include ones in which a number of misconceptions may manifest themselves. For example, the belief that an object will go in the direction in which it is kicked *irrespective* of the body's velocity. This belief can be seen as an example of a stored procedure which may be associated with dynamics[6] but a precondition that makes the belief correct is missing —namely, that the body must be at rest. DYNLAB can be used to express this faulty belief very easily but it is more difficult to say what freedom the student should be given to express a more reliable conception. Certainly, the incorrect belief needs to be guarded by the condition that the body be at rest but it is not sufficient to stop at this point. A plausible procedure needs to be constructed which works for moving bodies.

One of the key problems is the idea of force as force of supply [Viennot 79] or motive force [Watts 83]. The belief that a body possesses a supply of force (akin to energy) due to its motion which gradually gets used up is widespread. DYNLAB can be used to model such a belief as the student may be asked to model a situation in which a body is to move with constant speed. If the student believes that the body must also have a force associated with motion then s/he might wish to try to drive the body with some force function.

Another situation which students are asked to model using DYNLAB requires exploration of a simple relation between two inertial frames of reference (see figure 4–10 for the example used). If one of the frames is perceived to be at rest —the 'privileged' frame of the observer— then the student can be asked to arrange certain things to happen in the other frame which may be reinterpreted by the student in interesting ways. The student might be regarded as being weak at envisioning the appearance of things in the moving framework though Saltiel and Malgrange point out that there are far more complex issues here then poor envisionment [Saltiel & Malgrange 80], for example, a failure to see velocity as a function of reference frame and object.

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[6]DiSessa suggests that the procedure may be *distributed* or, in other terms, not linked properly with the overall knowledge structures that are relevant for dynamics [diSessa 82].

The tendency to ascribe velocity as a property of the object is reinforced by the common formalisation of the *state* of a body which reasonably leads students to believe that if an object has a mass and if both mass and velocity are part of the state of the object then the object *has* a velocity. Unfortunately, the current version of DYNLAB may well not help break this erroneous belief. On the other hand, it is possible to draw attention to the phenomenological evidence.

4.3.4 Other Modellable Misconceptions

Apart from a number of such interesting dynamics situations that were modelled with DYNLAB by students it is worth pointing out that a fair number of standard investigations can be undertaken to discover, for example, the relationship that exists between impulse, velocity and mass, the triangle of forces, resolving forces into components, relationship between force of gravity near the earth's surface, mass and acceleration, projectile motion and more.

Two investigations which might be performed will now be described. One concerns Newton's Third Law and the other the distinctions between speed and velocity and distance and displacement.

Newton's Third Law

DYNLAB can be used to control the motion of two distinct bodies (point masses). Newton's Third Law is not programmed into DYNLAB so, if they happen to meet, the two bodies would simply pass through one another. The student could be asked to model this situation but is required to add impulses that constrain the bodies properly.

A more standard approach might involve starting with two blocks resting on a table with one block on top of the other. The student models this situation by describing the table, the two bodies and the force due to gravity acting on the bodies. Both bodies proceed to sink through the table. The student defines the force of the table on the lower block[7] and, eventually, all that is wrong is that the top block falls through the bottom block and the table! Now the student has to apply Newton's Third Law to the interaction between the two bodies. This non-trivial exercise permits the student to construct a theory in parallel with the use of DYNLAB.

We can use Maloney's analysis of misconceptions as the basis for setting up situations similar to figure 4–2 in which two bodies are accelerated along a smooth horizontal surface by applying a force of 10 Newtons to body B. If

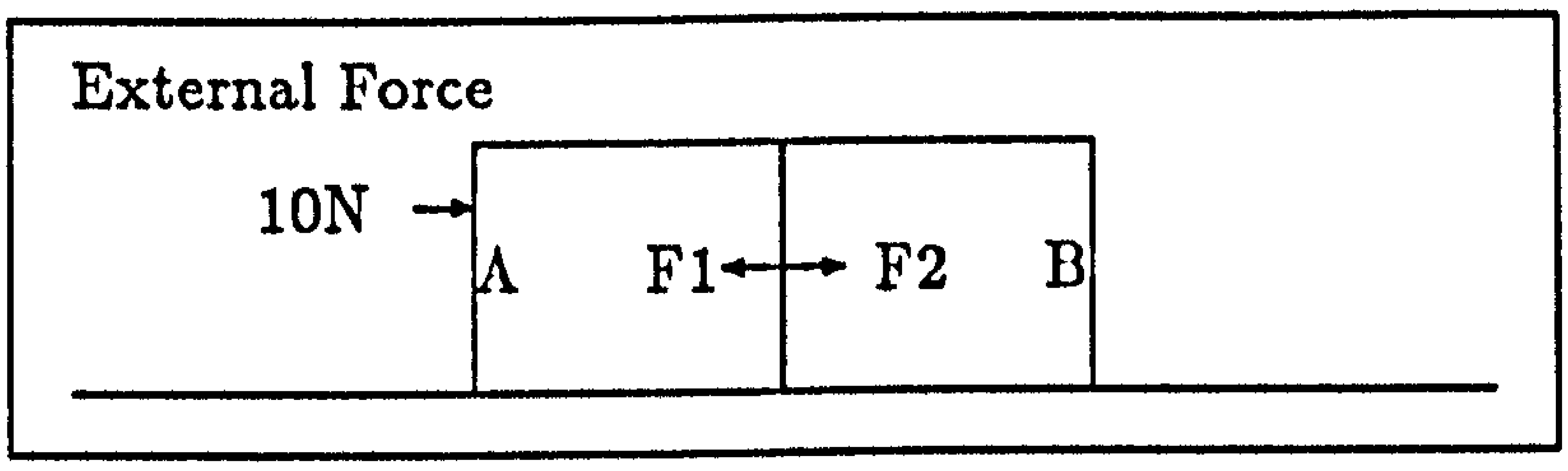

Figure 4–2: When Two Bodies Collide

the mass of body A is given as much greater than that of body B then we might reasonably expect some students to believe that F2 is greater than F1. Other situations can be constructed to explore a sequence of development of increasingly sophisticated misconceptions.

This approach to modelling demonstrates the principle that a complex physical situation should be explored by breaking some key relationship and requiring the student to investigate ways of putting the missing link back.

Scalar/Vector Confusions

Untangling confusions associated with indistinct concepts is awkward. It is reasonable to suggest that students should be placed in situations where differences become manifest. For example, consider the concepts of speed and velocity. The

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[7] An interesting moment if the student thinks the table acts on both blocks.

magnitude of the velocity is *not identical* with the speed. This point is made forcibly by Warren —for example, page 1 of [Warren 79].

An example of how DYNLAB might be used to investigate one aspect of this problem follows. The student could be required to move a body around a path

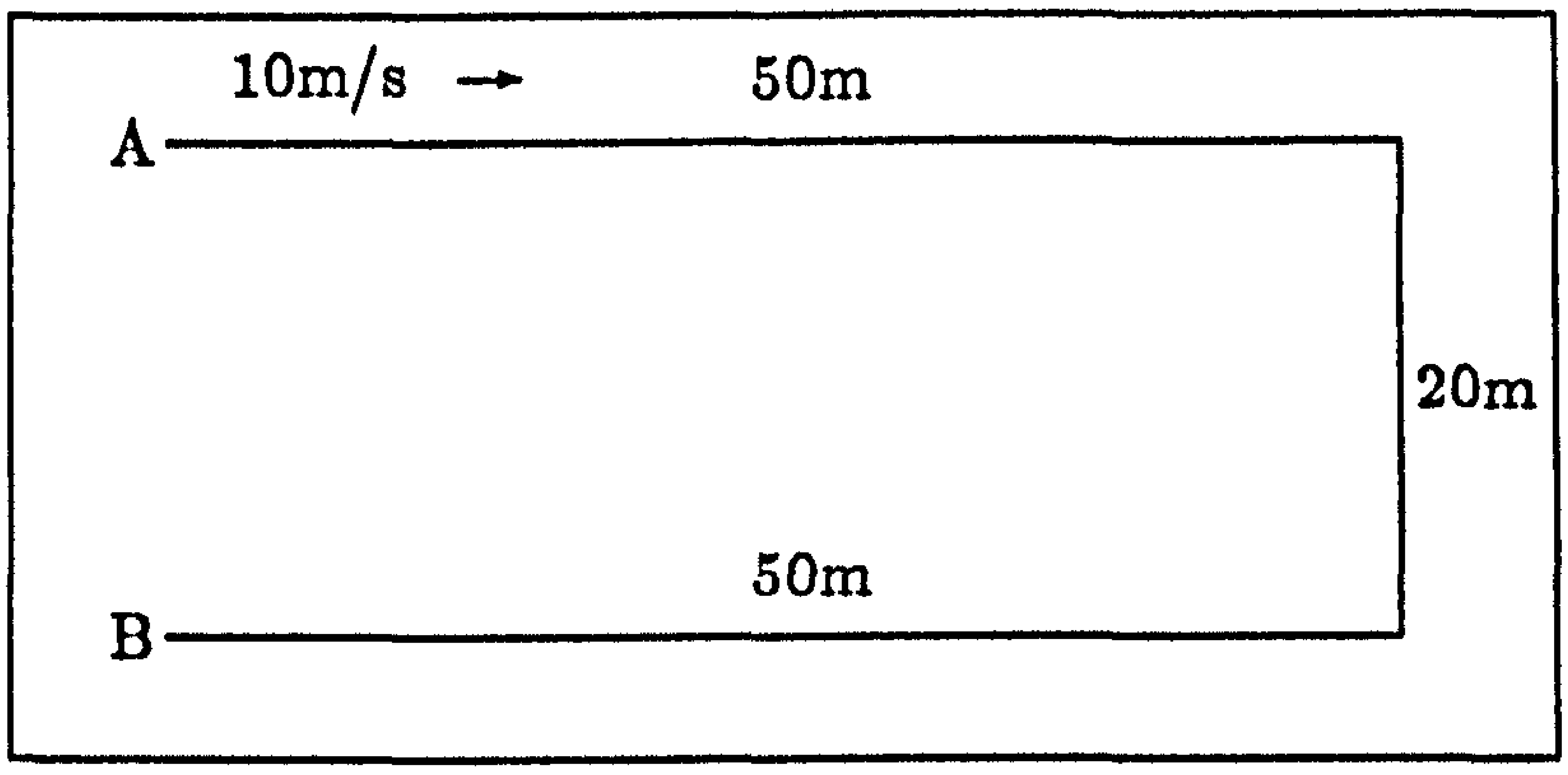


Figure 4–3: What is the Magnitude of the Change in Velocity?

so that the body ends up with the magnitude of the change in velocity of $20m/s$. The student who misunderstood this as asking for a change in speed of $20m/s$ might arrange for the body to be moving at $30m/s$ by the time it arrived at B. A correct solution would be to arrange for the body to arrive at B moving at $10m/s$. The only way the student is going to discover that they have confused two concepts will be if DYNLAB is able to print *both* the body's change in speed and the magnitude of the change in velocity.

4.4 The Design of DYNLAB

DYNLAB is a *Dynamics Laboratory* written in APPLE PASCAL to run on an APPLE II computer with a language board and an optional printer. The design was begun in 1982. It was coded during the winter of 1982/3 and used by students in the summer term of 1983.

4.4.1 An Overview

Diagram 4–4 provides a schematic overview of the computer system DYNLAB.

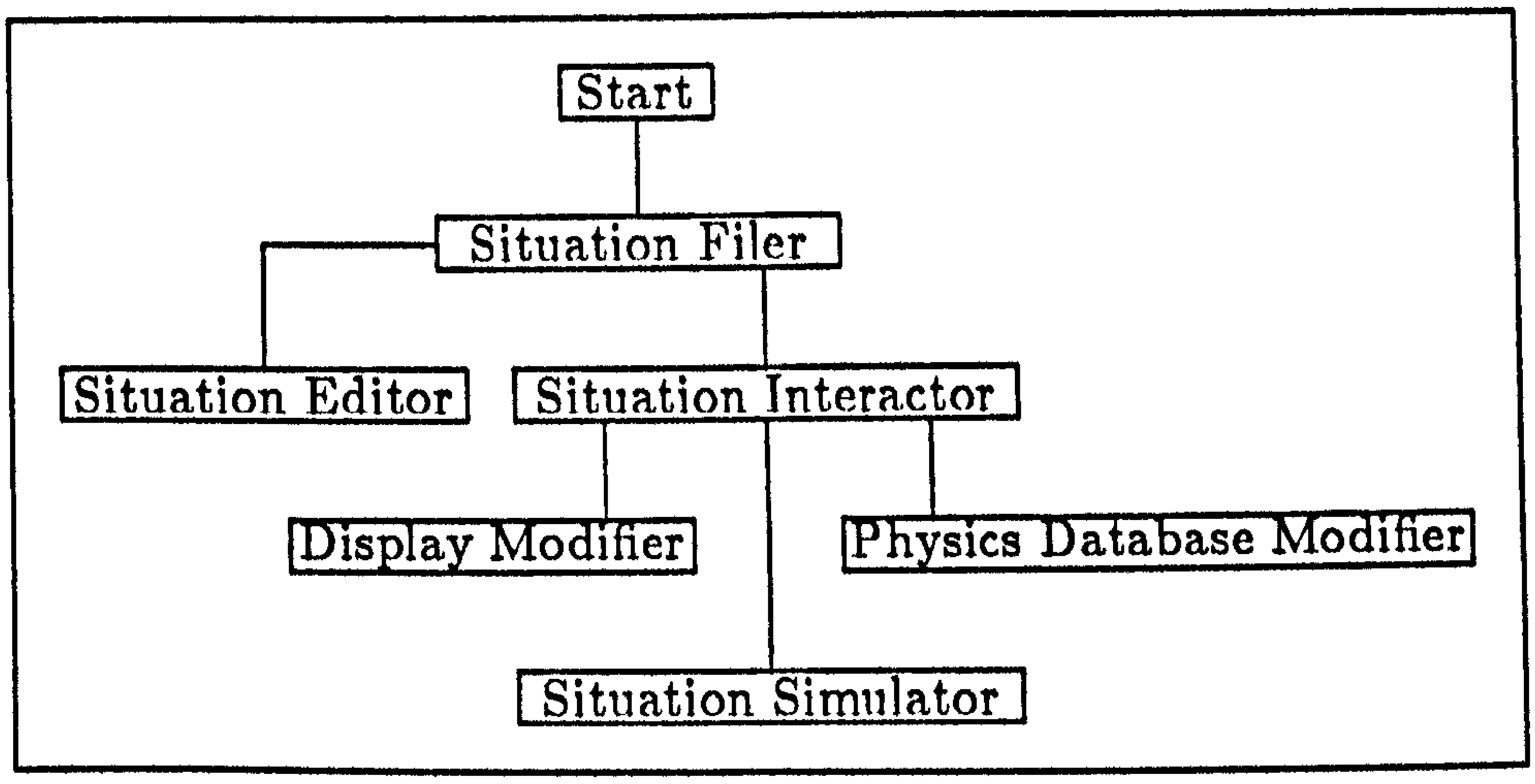


Figure 4–4: An Overview of DYNLAB

A *situation* is a complete description of some dynamics problem to be explored. This description is organised in terms of three types of object:

- MAP: A description of the territory over which the object is to move

- JOURNEY: The features of an object[8] that are to move —basically, either a set of constraints on the object or a description of interesting events

- FORCE: The information needed to drive the object around the MAP subject to the constraints of the JOURNEY

The *Situation Filer* provides the means for choosing a specific situation, building or editing a named situation, deleting situations and so on.

The *Situation Editor* operates on a named situation. The situation can be thought of as a workspace in which various MAPs, JOURNEYs and FORCEs exist. Some of these objects are active and others passive. It is only the active objects that form the situation that will eventually be simulated. The active/passive concept is provided as a convenience to allow greater conceptual flexibility when experimenting with a situation.

The *Situation Interactor* provides the equivalent of an interactive interpreter. This enables the student to run the *Situation Simulator*, change some features of the situation (through the *Physics Database Modifier*), tailor the output (via the *Display Modifier*) in a simple way.

Basically, the *Physics Database Modifier* operates on the active objects defined by the situation and is similar to editing an object in the workspace.

The *Display Modifier* is used to provide a wide range of information on the simulated journey —including a number of graphs while the *Situation Simulator* is used to *run* the situation.

Throughout the use of DYNLAB there is a conscious attempt to exploit the metaphor of object oriented programming.

4.4.2 The Domain

The concepts incorporated are those associated with the dynamics of one or two point masses. This includes:

Mass	Displacement	Velocity
Acceleration	Force	Impulse
Gravity	Time	

[8]There may be two objects —each requiring a separate JOURNEY.

It was a design decision to avoid any explicit reference to the concepts of:

Distance	Speed	Weight

As far as it proved practicable, if a quantity is a vector quantity then this quantity is always associated with both a magnitude and a direction. This has a number of implications, one of which is that a distinction is made between the magnitude of the velocity of a body and its speed.

It was also decided to require students to input units along with any value for a quantity. This has the consequence that students must be reasonably familiar with the units for the basic concepts before using DYNLAB. Some comments about this will be made in section 4.6.2.

4.4.3 How to Use DYNLAB

The model here is based on that observed by Howe for children learning to program in LOGO. Children first use programs, then borrow clever ideas from others and finally move on to develop their own programming style [Howe 77]. Students start with pre-programmed situations, learn how to modify them and go on to create their own.

Simple Usage

The students are expected to receive some guidance as to what they should attempt to do. The worksheets provided with DYNLAB are designed around the cycle

$$\text{RUN} \quad \overset{\longleftarrow}{\longrightarrow} \quad \text{DEBUG}$$

The student is offered a number of situations that have been pre-built. For each such situation there is an accompanying worksheet. Once the student has selected the situation then s/he runs the simulator which produces a dynamically updated analogue model and, as a default, prints out the velocity of the body —both magnitude and direction.

The run is over if the student terminates it, some time limit is exceeded or some space limit is exceeded.

Advanced Usage

The cycle is now

$$\text{BUILD} \longrightarrow \text{RUN} \;\underset{\longrightarrow}{\overset{\longleftarrow}{}}\; \text{DEBUG}$$

This involves the student constructing programs that determine how objects are to move. There may be worksheets designed to guide the student but there is no reason why students should not ultimately be able to design their own situations according to their own interests.

4.4.4 Writing Programs

Programming DYNLAB involves a number of stages:

- Describing the Map
- Constraints on the Object
- Programming the Object to Move

In order to see how this is done, imagine trying to describe an icecube sliding across a horizontal table top with no friction and then falling off the end (see figure 4–5). We will name the situation *SLIDE*. Now we have to define the MAP, JOURNEY and FORCE aspects of the situation. For the MAP, we have to make some decisions about how far the ICECUBE is initially from the edge of the table and on what 'bearing' the edge is from the start position. Here is a definition of the MAP which we name *TABLETOP*:

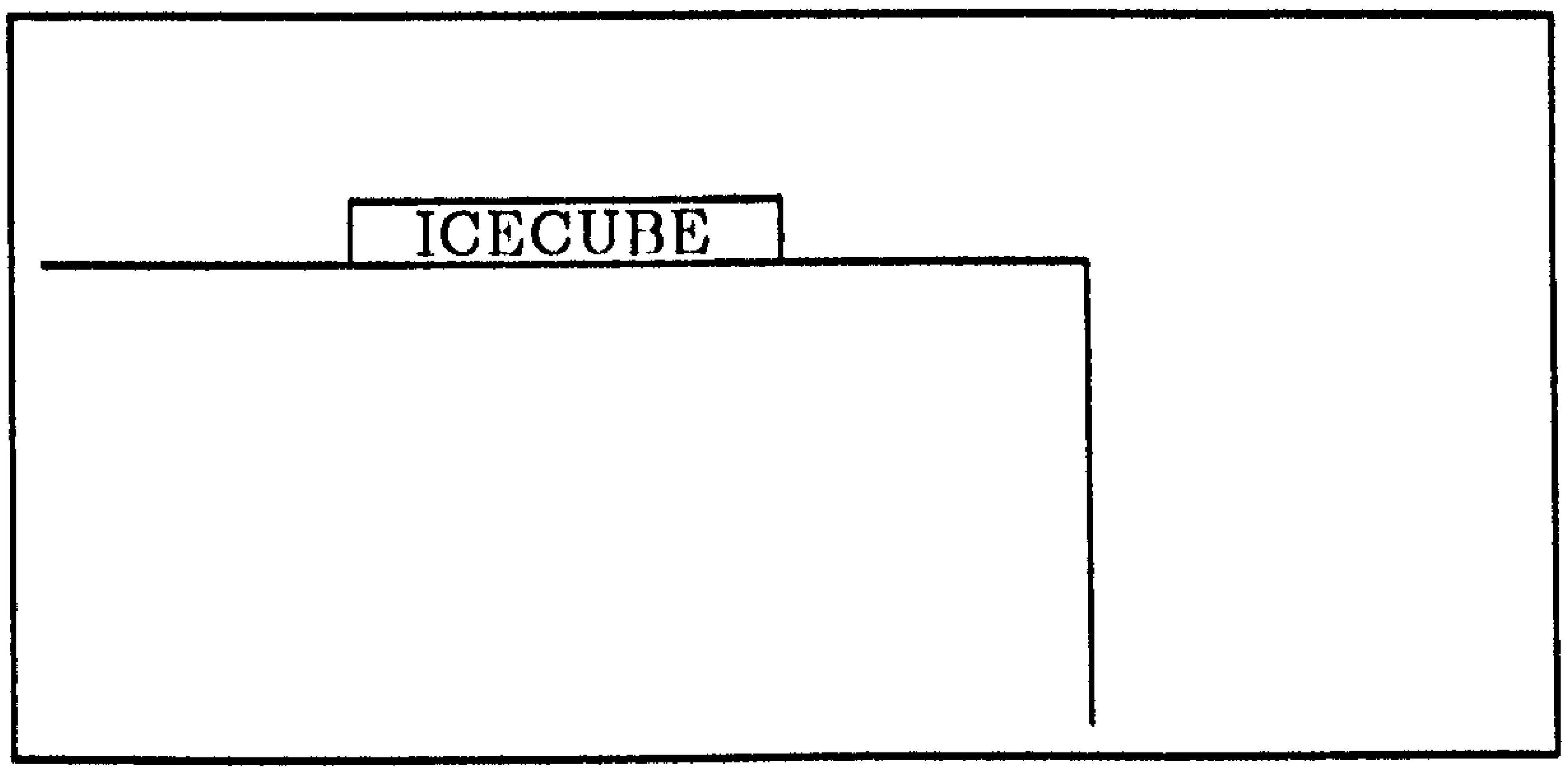


Figure 4–5: Modelling an Icecube Moving

SLIDE:MAP:TABLETOP

DISPLACEMENT	BEGIN	EDGE	10M	90
DISPLACEMENT	EDGE	FLOOR	20M	180
JOIN	BEGIN	EDGE		
JOIN	EDGE	FLOOR		

We have also had to define three places, *BEGIN* for where the ICECUBE starts from, *EDGE*, for the edge of the table and *FLOOR* for the point on the floor immediately under the edge of the table. It is tempting to name the starting position as ICECUBE but we must distinguish between fixed places and moving objects.

Now for the *JOURNEY* named *SLIDE*.

SLIDE:JOURNEY:ICECUBE

START	BEGIN		
MASS	2KG		
VELOCITY	BEGIN	2M/S	90

If the MASS statement is missing the system assumes a default mass of 1Kg. If the VELOCITY statement is absent then a default of 0m/s is assumed.

There will be a need for two forces. One will be the force on the icecube due to gravity and the other is the reaction of the table which lasts until the icecube falls off the end of the table. The force due to gravity we will call *WEIGHT* and the reaction we will name as *REACTION*.

```
SLIDE:FORCE:WEIGHT
ACTS        ICECUBE
FORCE       ONE          19.6N  180

SLIDE:FORCE:REACTION
ACTS        ICECUBE
FORCE       ONE          19.6N  0
            DISPLACEMENT        10M
```

The *ACTS* command determines which objects the FORCE acts upon. In the definition of WEIGHT, the FORCE command requires a label to distinguish the order of several such commands in a sequence. The label is equivalent to a line number. The FORCE command in the definition of REACTION needs to be conditional: it must apply only until the icecube travels 10M. The command can be read as saying

> There is a force of 19.6 Newtons vertically upwards until the magnitude of the displacement from the start is 10M

Note that the calculation of 19.6 Newtons is the only one that is necessary and that even this can be avoided by a facility provided by the *Physics Database Modifier* which permits a constant gravitational field to be switched on thus making WEIGHT redundant.

4.4.5 System Messages

Syntactic errors are caught at the time when a command is issued rather than at run time whether or not the student is using the Situation Editor or the Situation Interactor. The error messages were designed to fit in with the object oriented programming metaphor.

A set of *success* messages were also incorporated on the principle that any attempt to change some object for which there is no immediately visible effect must be provided with some consequential message to let the student know that the change was effected.

4.4.6 Support Materials

A number of different sorts of support material were provided. A manual explaining the system, a set of six introductory worksheets, a set of five worksheets exploring the idea of impulses, a set of seven worksheets on the concept of continuous forces, a set of five worksheets based on the misconception test and four worksheets of ideas for more open ended work and some other material.

Not all the material was used in the observational period. In part, these materials were constructed to explore the flexibility of the system.

4.4.7 The Simulation

As has been said before, the simulator can produce a dynamically updated analogue model on the TV screen attached to the computer. It can also provide a number of dynamically constructed graphs at the request of the student.

Various features are under the control of the student. For example, names of places on the screen can be displayed or the places simply marked with a +. Also, the facility to leave tracks to indicate the paths that the objects take as they move can be switched off or on.

An important facility is the ability to switch gravity on and off. If gravity is on, the effect is equivalent to a FORCE which ACTS on all defined objects in such a way that is equivalent to the constant gravitational field so common to school physics courses.

A trace facility which can be switched on or off is also provided. The trace includes any data requested by the user together with some extra commentary by the system on events of interest. If the trace is on, then the trace data can be examined afterwards or printed out. Figure 4–6 is an example for the situation illustrated in figure 4–5: The "..." indicates additional comments from

```
                    PRINTOUT OF:
1:ICECUBE VELOCITY IN M/S
TIME(S):0
1:MAG=2          DIR=90
...TIME(S):0
...ICECUBE AT BEGIN WITH REQUIRED VELOCITY

TIME(S):1
1:MAG=2          DIR=90
```

Figure 4–6: Tracing an Icecube Moving

DYNLAB over and above the information requested by the student. MAG is short for magnitude and DIR for direction. The "1:" indicates the information stream number.

The student can select whether to print out data or not. If data is printed out it can be of various sorts. It can be the data for a named object's

- Displacement
- Velocity

- Acceleration
- Average Velocity since the start
- Average Acceleration since the start

There can be one or two separate streams of data. The limitation is due to the screen size of the APPLE II.

The student can also elect to examine a graph of some object's behaviour in terms of two of any of:

- Magnitude of Displacement
- Magnitude of Velocity
- Magnitude of Acceleration
- Time

Displays can be easily rescaled and graphs overlaid.

Further utilities permit the student to get help in the form of brief extracts from the manual, inspect the *Physics Database* and examine the current *Display* state. The *Display* state includes information about the scale settings for various quantities, whether full place names are used, whether tracing is on, whether tracks will be displayed, what variables for which object are set up for graphing, whether the graph option has been selected and which information is to be printed on the screen during the main simulation. A summary of the DYNLAB command language syntax can be found in appendix G.

4.4.8 Comments on the User Interface

There is no doubt that the user interface needs improving: there are several features which ought to be changed.

The basic problem is the complexity of some of the commands. For example, here is about the worst case possible during the interactive phase:

+ REACTION FORCE TWO 5N 90 INCREASE VELOCITY 5M/S

where this means:

> Add a force component labelled "TWO" to the FORCE named REACTION of 5 Newtons at an angle of 90 degrees which will be active (after any previous force is deactivated) until there has been an increase in the velocity of 5M/S for any object upon which REACTION acts

It is clear that a better approach would be based on template editing such as that featured in [Gould & Finzer 82].

It is also too difficult to move between, for example, the Situation Editor and the Situation Interactor. Even though the student can use the Situation Interactor to modify the *Physics Database* in ways much like those used by the Situation Editor there are some things that cannot be done through the System Interactor. For example, the student cannot make changes permanent and cannot deactivate a complete FORCE.

Even using the Situation Editor is limited in that the student cannot quickly borrow, for example, a MAP used in Situation A and a JOURNEY from Situation B and use them in Situation C. Also, a better editor would allow the removal of the labels currently required to define the force components in a FORCE.

Finally, JOURNEY might well be renamed to reflect that it represents the journey of an individual object. Perhaps JOURNEY should be renamed as OBJECT? There is also possible confusion between the FORCE and the component named FORCE that may be part of the FORCE. A better name for the FORCE would indicate that it is allied to that which causes the journey. Perhaps FORCE should be renamed ACTOR or IMPELLER?

4.4.9 Discussion of the Design

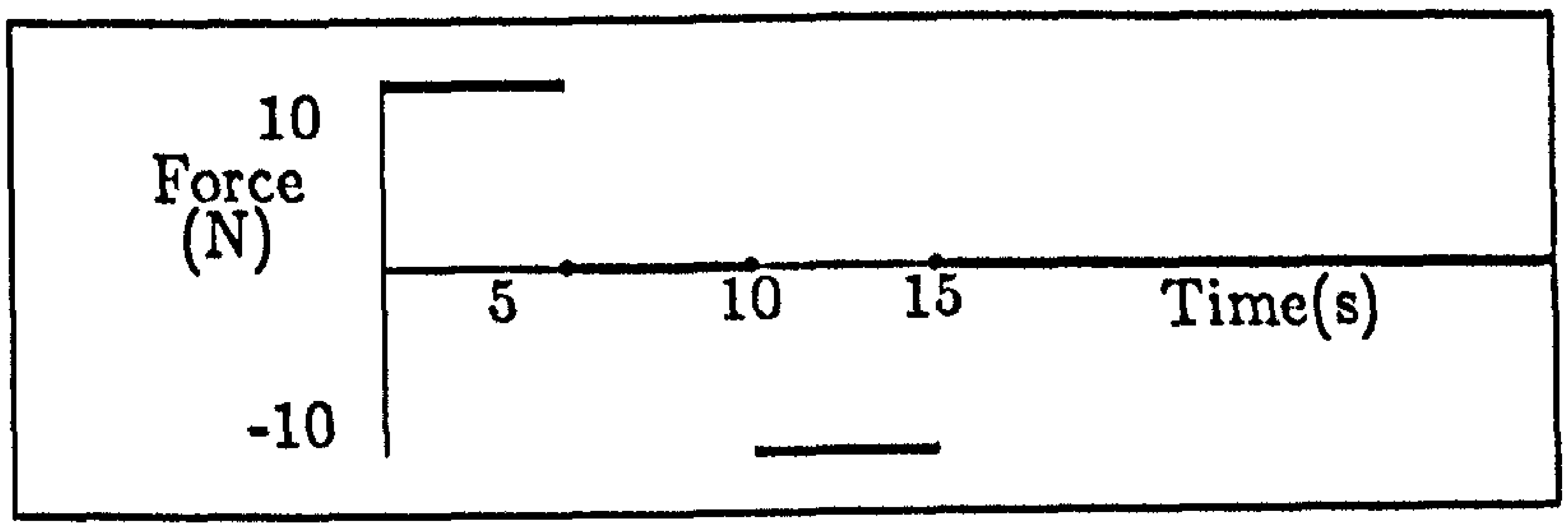
Some of the issues underlying the design will now be examined. The discussion will be organised around the topics of force, momentum and graphs.

The Basic Principle The general design principle was to provide force functions at least as complex as those required to be understood by the students for which DYNLAB was targetted using the normal school curricula. There were, however, some restrictions. For example, DYNLAB did not allow completely general descriptions of force functions. There is no reason why generality should not have been included except that it was not needed for the experimental environment.

The lack of generality does, however, lead to limitations. For example, to model the mutual gravitational attraction of two bodies would require the student to be able to define the force function so that it depended on the distance these bodies are apart. This cannot be done with the current version of DYNLAB.

For the most part, forces are thought of as the result of some causal agent acting on some object. The system, however, does not allow a physical object to apply forces directly to other physical objects. If a body is to exert a force on another body then the force must be given a separate, independent existence and told to act on the other body.

The Range of Possibilities The specific concepts chosen can be explored provided motion can take place in two dimensions and that it is possible to apply constant forces. This turns out to be inadequate for the kinds of one dimensional problem that students are often expected to handle. For example, a straight line journey in which an object accelerates uniformly from rest, travels with constant velocity for a while and eventually decelerates uniformly to rest. This requires the force acting on the object to be a step function —see figure 4–7. Even for quite simple straight line motion students are expected to be able to handle force as a step function rather than a force that is constant. To define



$F(t) = 0N \quad , t \leq 0$
$F(t) = 10N \quad , 0<t<5$
$F(t) = 0N \quad , 5 \leq t \leq 10$
$F(t) = -10N \quad , 10<t<15$
$F(t) = 0N \quad , t \geq 15$

Figure 4–7: A Simple 'O' Grade Problem!

the same function for DYNLAB[9]:

FORCE	ONE	10N	0
(until)	TIME (is)	5S	
FORCE	TWO	0N	0
(until)	TIME (is)	10S	
FORCE	THREE	-10N	0
(until)	TIME (is)	15S	

assuming straight line motion in the direction represented by 0 and that no definition is needed before the start of timing.

Defining Acceleration So far the assumption has been that it is essential to apply a force to a body to 'cause' a change in velocity which, in turn, causes a change in position. In 'O' grade work, however, it is likely that the rôle of force is not made explicit until the student has dealt with the kinematics of journeys.

[9] The statements in brackets are not part of the original text but are added for clarity by the system.

DYNLAB could be used to explore the kinematics of journeys provided that it is possible to set an acceleration function rather than a force function. Should students first try to manage journeys by setting an acceleration function? Using similar terminology to that of Lovell who has assessed certain scientific concepts in terms of a Piagetian developmental theory [Lovell 74], the concept of force is at a level of abstraction above that of acceleration. This is due to the nature of the equation that links force to acceleration

$$F = m\,a$$

and, partly, to the belief that the determination of the mass (or acceleration) of a body is easier to handle by means of one's intuitions than the estimation of the force applied to the body.

In interviews with students it is apparent that the word *force* is used to describe events very frequently [Osborne & Gilbert 80a, Osborne & Gilbert 80b]. It is argued here that students do not naturally infer the existence of a force from the apparent departure of a body's motion from Newton's Laws. This would require them to be in possession of a clear understanding of Newtonian dynamics. The reality is usually otherwise. Watts, for example, has described eight different kinds of force which he associates with students' alternative frameworks [Watts 83]. To quote one example:

> Objects restrained in a position have force

so that a golfball at its maximum height is subjected to a force down *and* an equal force up. This work influenced the design of DYNLAB in that it is some notion of force that needs exploration before necessarily exploring the problems associated with acceleration.

The Place of Momentum

Justifying the Use of Momentum If the student is to create sudden turns in the path of some object then the concepts of momentum and impulse are needed. Now the first thing to notice is that impulse is not part of some syllabi (for an example see [SEB 82]). It may also be said that if force is a very abstract quantity then impulse is even more abstract in that:

$$I = F\ t$$

and therefore impulse (or change in momentum) should not be introduced. McCleland, however, recommends that arguments based on impulse and momentum should be promoted as a means to the explanation of the interaction between bodies [McCleland 75]. Mention has already been made of Raven's work which indicates that primary school children have some grasp of the momentum concept [Raven 68]. Again, it is not argued that a complete understanding exists but that intuitions exist prior to formal teaching which may be more valuable to explore than whether or not a student can recall the above formula and solve for one unknown in terms of two given quantities.

A LOGO Approach? The problem is how to get the student to communicate that a KICK (impulse) should be applied at some angle. There would seem to be three possible ways this could be done:

Use Landmarks When you reach point A apply a KICK directed towards point B

Use Bearings When you reach point A apply a KICK on bearing 090 degrees

Use Relative Turns When you reach point A turn clockwise through 90 degrees and apply a KICK

The first of the above approaches would be difficult in practice as any requirement to change the direction of the KICK slightly would mean adjusting or creating a landmark. The serious contenders are the use of bearings or the LOGO-like idea of specifying a turn followed by a KICK.

The implications of the LOGO approach include a requirement that the student knows the direction of motion in order to decide what to do. This would not seem too difficult. A further problem is that the application of the KICK requires two commands —a TURN of some sort followed by a KICK of some magnitude. The concept of KICK is still a vector concept but it has been separated into components. The decision taken was to adopt a 'bearings' approach.

The Use of Graphs

Graphs pose a particular problem in that most of the reported difficulties in the research literature are connected with the *interpretation* of graphical data. Yet Rae, for example, concludes after a detailed study of the problems found in teaching the concept of acceleration that teachers should consider using graphical methods in the teaching of acceleration to a greater extent than at present [Rae et al 77].

A design principle adopted for DYNLAB is to permit students the freedom to choose to examine the construction of a graph as an alternative to the display of bodies moving in a two dimensional space. They are free to graph a variety of quantities and to choose which quantity is to be represented by the x-axis and which by the y-axis. The student is also able to control whether or not to overlay one graph on top of another of the same sort.

It might have been expected to automatically scale the graph so that no point is plotted outside the available space but it was believed that greater learning opportunities existed if the student was made responsible for the scaling of axes. A potentially fruitful way of learning about dynamics is by building up a set of expectations about the likely ranges of the magnitude of displacement, velocity etc that are implied by some environment.

One limitation of the decision to stress vectors is mentioned. Because the quantities that can be graphed are magnitudes they are never negative. This means that the graph of the magnitude of velocity against time for a ball thrown vertically upwards will look quite different from the 'standard' graph of velocity against time.

4.5 Observations on DYNLAB Users

4.5.1 Observational Objectives

The production of the Dynamics Laboratory is not an end in itself. There are at least three reasons for its existence which will now be recapitulated.

The Demonstration of Dynamics Principles: DYNLAB can be used to illustrate certain dynamics principles —but we would like to know which principles might have been sensibly included and which ones it would have been impossible to incorporate.

The Construction of Experiments: The extent to which students —aided or unaided— can construct their own experiments. The problems they encounter as they attempt to model various features of some initial problem. Whether their attempts to incorporate their own misconceptions into their model are successful.

The Effect of the Feedback: Whether students can detect whether they have a model which satisfies the original specification. The extent to which they attribute a discrepancy to the system rather than to their own internal model. Whether they can be said to learn from their attempt to model a situation. Whether their perception of events in the real world is so distorted that their own faulty model is seen as correct.

We also have some high level educational questions to consider:

The School Curriculum: How well Does DYNLAB fit into the curriculum. The effects that its use might have on the sequence and timing of teaching various physics topics

The Classroom: The skills needed by the classroom teacher to use DYNLAB successfully. The management problems that will occur.

The Support Materials: To what extent they were successful and in what ways they can be improved.

The above questions are, of course, not the only ones of interest. We have to ask questions about the system itself.

The Student's Model of the System: The extent to which students have a clear picture of the hierarchies within the system. Do they get confused when they try to do something at the wrong level?

Extraneous Features: Any features which turn out to have no utility. The improvements needed to the HELP subsystem.

Error Reporting: Whether the error messages are helpful. The improvements that are needed to the error reporting mechanism.

Of the above, it is the student's model of the system which is the most interesting. Errors can (mostly) be removed, error reporting improved and some useless features extracted but if the system's construction does not match the user's intuitions then there may be some major problems that are not easily resolved.

It may be worth saying now that some of the students were distinctly computer-naive in that they had neither programmed nor used CAI programs —according to their own testimony. This certainly made it harder for the students to use the system.

4.5.2 The Experimental Setup

The initial concern was to get some feedback that would provide some preliminary answers to the above questions about the utility of DYNLAB.

With unlimited amounts of time and resources, a more formal design would have been produced but, in the circumstances, it was felt that a short and informal observational period would provide some useful information.

A local boys school was found —Daniel Stewart's and Melville— that was willing to cooperate for three weeks at the end of the Summer Term, 1983. All the boys were in S4 and had recently taken their Physics 'O' grade examination. Unfortunately, the school was not co-educational. It must also be noted that the school has an above average intake academically. See Appendix H for their eventual 'O' grade Physics results.

Ten boys were selected across the ability range to work with the system. The intention was to give each student a total of four hours observations. As two APPLE II's were available together with printers, two boys could be observed at a single time.

Their work was to be split into three parts:

The Misconception Test: The students were all to be given forty minutes to answer ten questions basically selected from the research literature on students' misconceptions in dynamics. The main criterion for selection was that the situation described by the question could be modelled reasonably successfully by DYNLAB. The questions were rephrased where necessary and put in a somewhat arbitrary order. The function of the test was to provide a crude assessment of their own models of a number of situations. This was useful as it provided a basis for observations made in the construction phase.

The Introductory Phase: A period of eighty minutes was to be used to introduce the students to some of the features of the system. A selection of worksheets was chosen from the twenty two or so that had been produced to demonstrate the kind of work that could be undertaken with the aid of DYNLAB. The ones selected could be divided into two categories: instructional and experimental. The names of the sheets selected were:

Intro:One	Intro:Two	Intro:Six
Kicks:Start	Kicks:Five	Forces:Four

A further function of this phase was that it was possible to concentrate on the observations pertaining to the software issues.

The Construction Phase: A period of two hours was therefore available for the next phase. During this period, the students would be permitted to take as long as necessary for them to model one or more of the situations selected from the misconception test. For simplicity, the order of questions was the same for each of them. The numbers of the questions from the test were:

ONE	EIGHT	THREE	FIVE	SEVEN

Worksheets were provided to give some less explicit guidance than in the introductory phase. It was hoped that it would take about forty minutes on average to complete each question —the actual average turned out to be about 47 minutes.

4.5.3 The Misconception Test

Each question is discussed in turn in terms of the results obtained from the students. It is worth pointing out now that roughly half the answers have to be interpreted as supporting the observations of previous researchers concerning misconceptions in dynamics.

Question 1

1. Jim is playing football when he receives a fast pass straight across the goal mouth. He wants to hit the ball into the gap at the bottom of the goal.

On the diagram, indicate roughly the direction in which he should strike the ball.

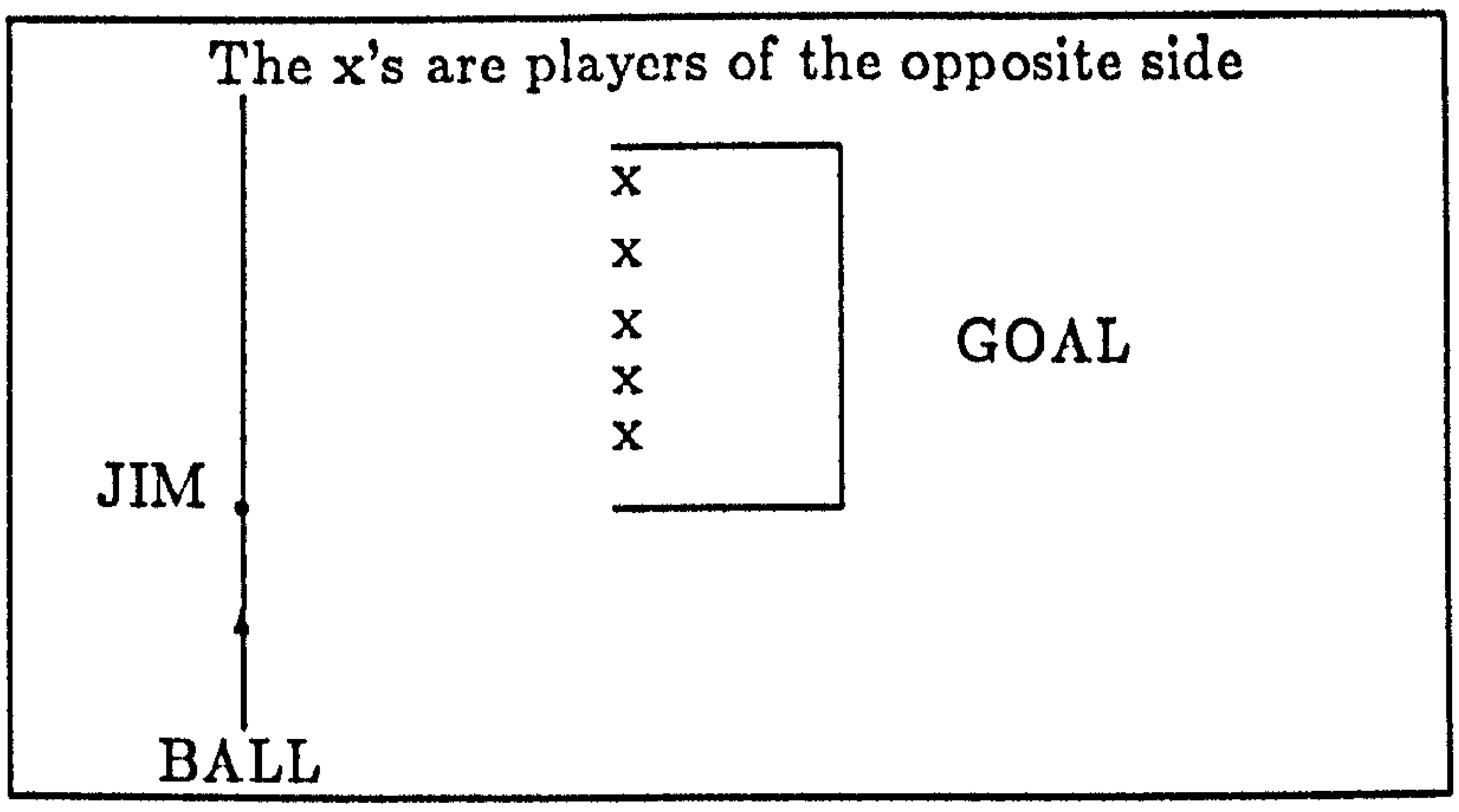


Figure 4–8: DYNLAB: Question 1

Both this question (figure 4–8) and the next one are essentially explorations of whether the student will use the *Aristotelian Corner* strategy described by diSessa in his work with the DYNATURTLE [diSessa 82]. The basic misconception seems to be that an impulse in a given direction will cause the body to go in that same direction —irrespective of the body's velocity at the moment of the impulse.

Of the ten answers, six were correct in indicating a 'backwards diagonal' kick and three fitted the misconception described above. A third involved what appeared to be a misinterpretation of the question in that a line was drawn from BALL to GOAL as if the player had kicked it at the location labeled BALL directly towards the GOAL.

Question 2

2. Jean is playing volleyball when she receives a pass from Jane parallel with the net.

On the diagram, indicate roughly the direction in which Jane punched the ball.

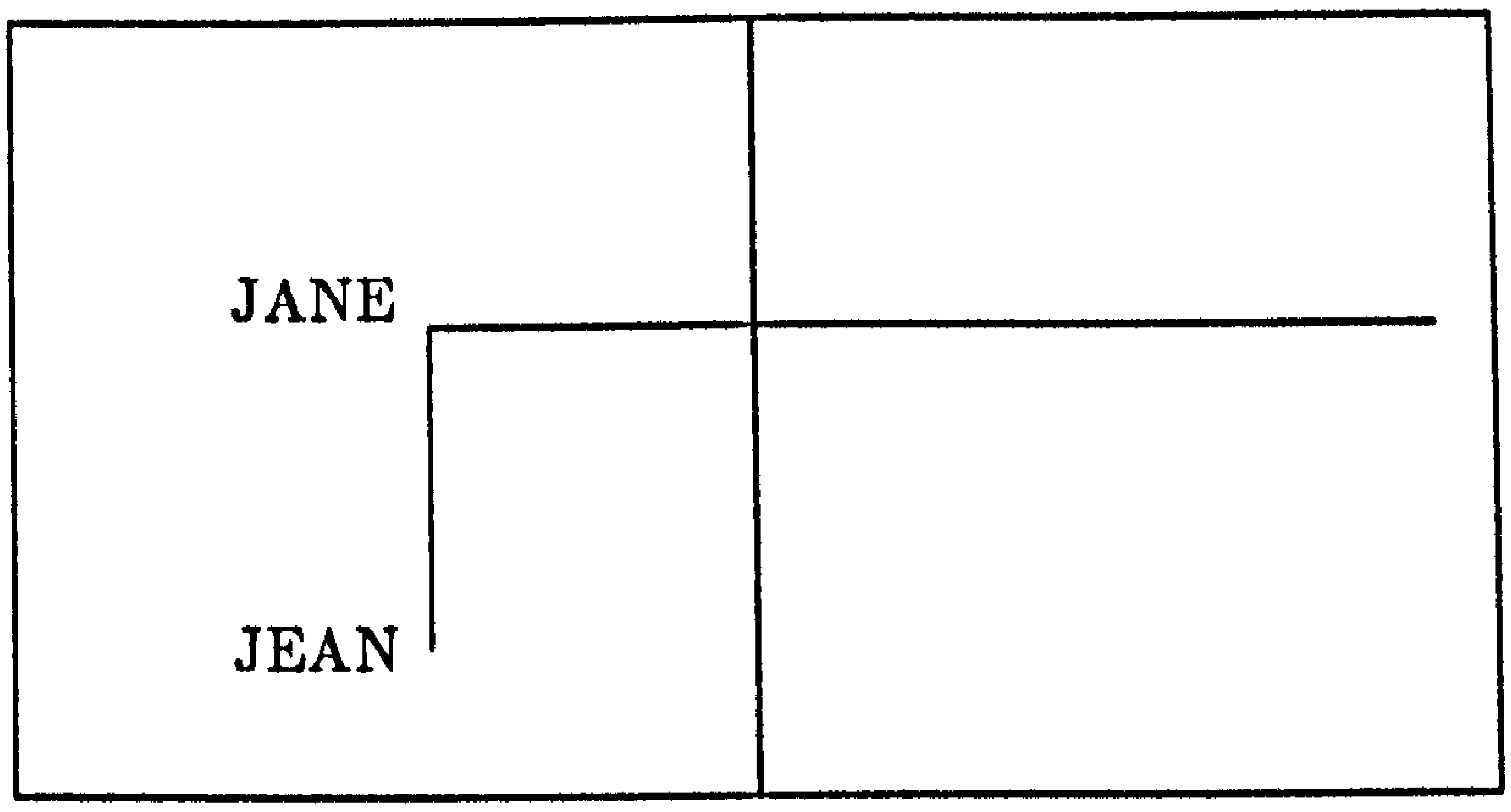


Figure 4–9: DYNLAB: Question 2

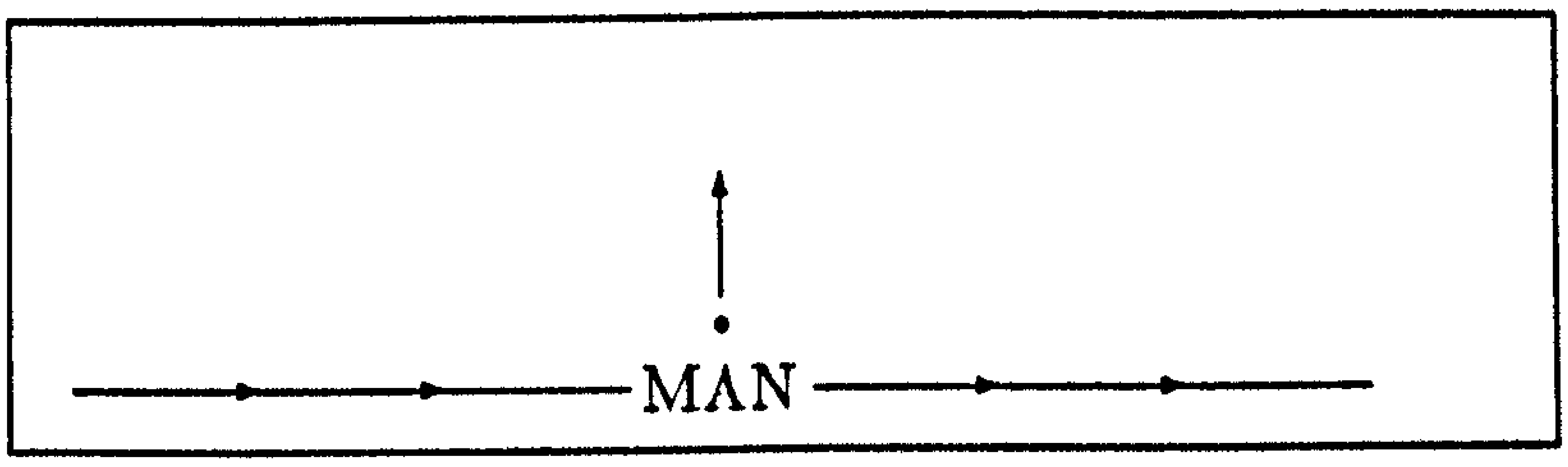
This question (figure 4–9) produced six correct answers —the same six students who answered the first question correctly. The remaining four appeared to possess the misconception described above.

Why are question 1 and question 2 so nearly the same? In the first question, the student was to infer the direction in which the ball was to be sent and then deduce the direction to kick. In the second question, the student did not have to infer the direction in which the ball was to be sent as this direction was already marked in. It was thought that this question would be slightly easier to interpret than the first one.

Question 3

This question (figure 4–10) is extracted from a situation described by Saltiel and Malgrange and applied to a number of students at University level

3. A man stands on a moving walkway and throws a ball vertically into the air.



Indicate which of the following happens:

1. The ball falls behind the man
2. The ball comes back to the man
3. The ball lands in front of the man

Figure 4–10: DYNLAB: Question 3

[Saltiel & Malgrange 80]. The results that were obtained indicated a common belief that the ball would fall behind the man. The very high figure of 90% was given for this misconception by Saltiel and Malgrange.

Of the ten answers obtained, three were correct in choosing option 2 and the other seven indicated that the ball would fall behind the man. Of the three that were correct, one initially indicated that the ball fell behind the man.

Question 4

This question (figure 4–11)was extracted with a small change from a paper by Clement [Clement 82]. Note that the diagram is slightly misleading: if the coin is thrown vertically upward then there should be no apparent sideways drift. These problems are inherited from Clement's own description [Clement 82].

His results indicated a tendency to ascribe two forces at B. One due to gravity and a larger one upwards. He reported a figure of between 80% and 70% for

4. A coin is thrown from point A straight up into the air and caught at C.

On the diagram draw one or more arrows showing the direction of each force acting on the coin when it is at point B.

Draw LARGER arrows for LARGER forces.

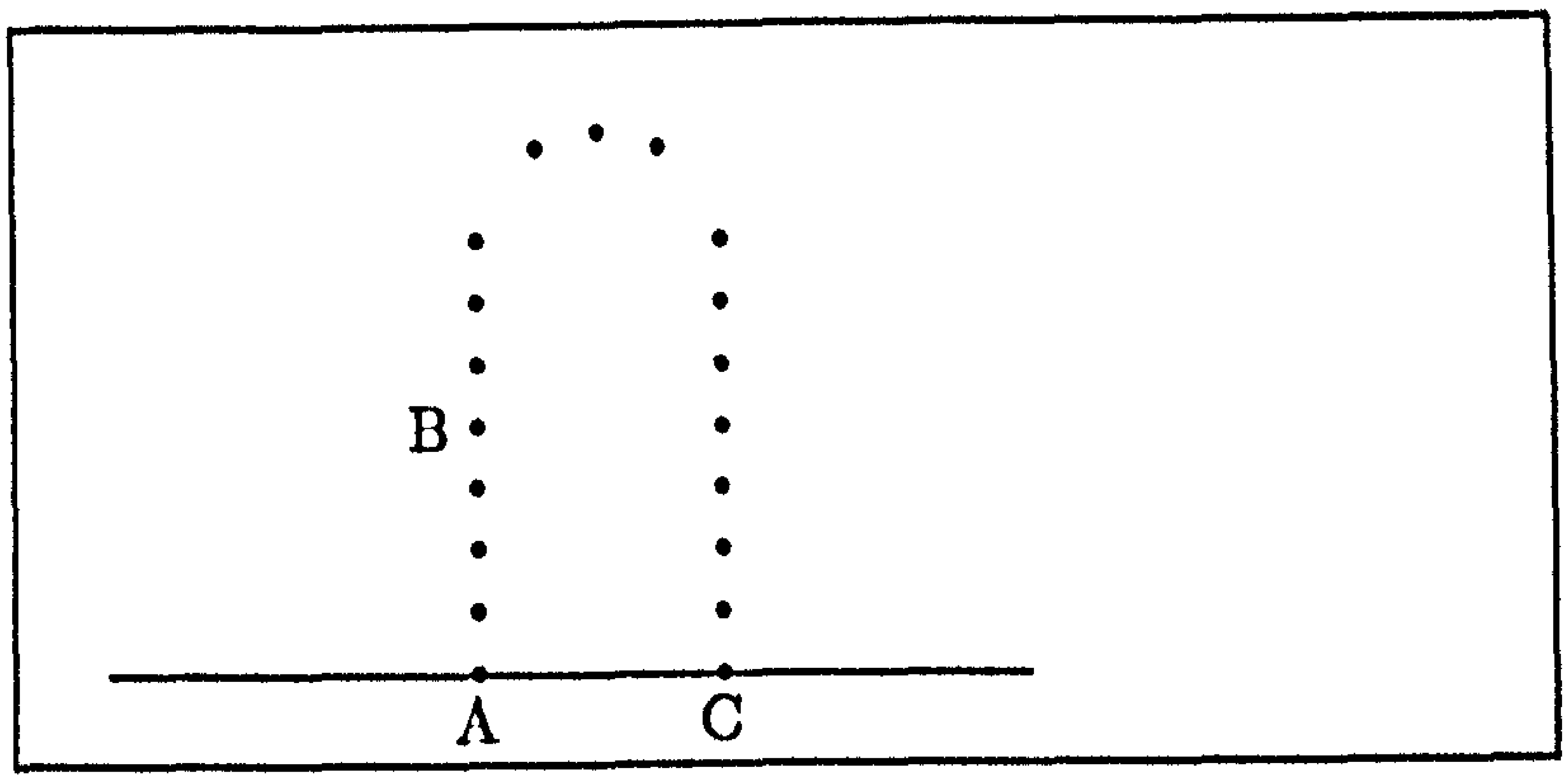


Figure 4–11: DYNLAB: Question 4

those who held this belief when tested both before and after a mechanics course respectively.

Two students did get this question right by marking in the force of gravity acting downwards but only after correcting their answers which were in agreement with the other eight in that they had more than one force acting on the ball at B. Of these eight, five had two forces acting and the other three had three forces —the extra one, in two cases, seemed to be a force to account for the sideways drift of the coin. The odd one out had two downward forces and one upward which seemed to be an attempt to distinguish between the upward and downward parts of the coin's journey.

Including the initial errors of the two who got the correct answer, eight marked the force up as larger than the force down and one the other way around. The remaining student produced an answer with one force up and one force down —but the forces were approximately equal.

Question 5

5. A rocket is moving sideways in deep space, with its engines off, from point A to point B.

It is not near any planets or other outside forces.

Its engine is fired at point B and left on for 2 seconds while the rocket travels from B to C.

On the diagram, draw in the shape of the path

a) from B to C

b) from C —remember that the engine is turned off now.

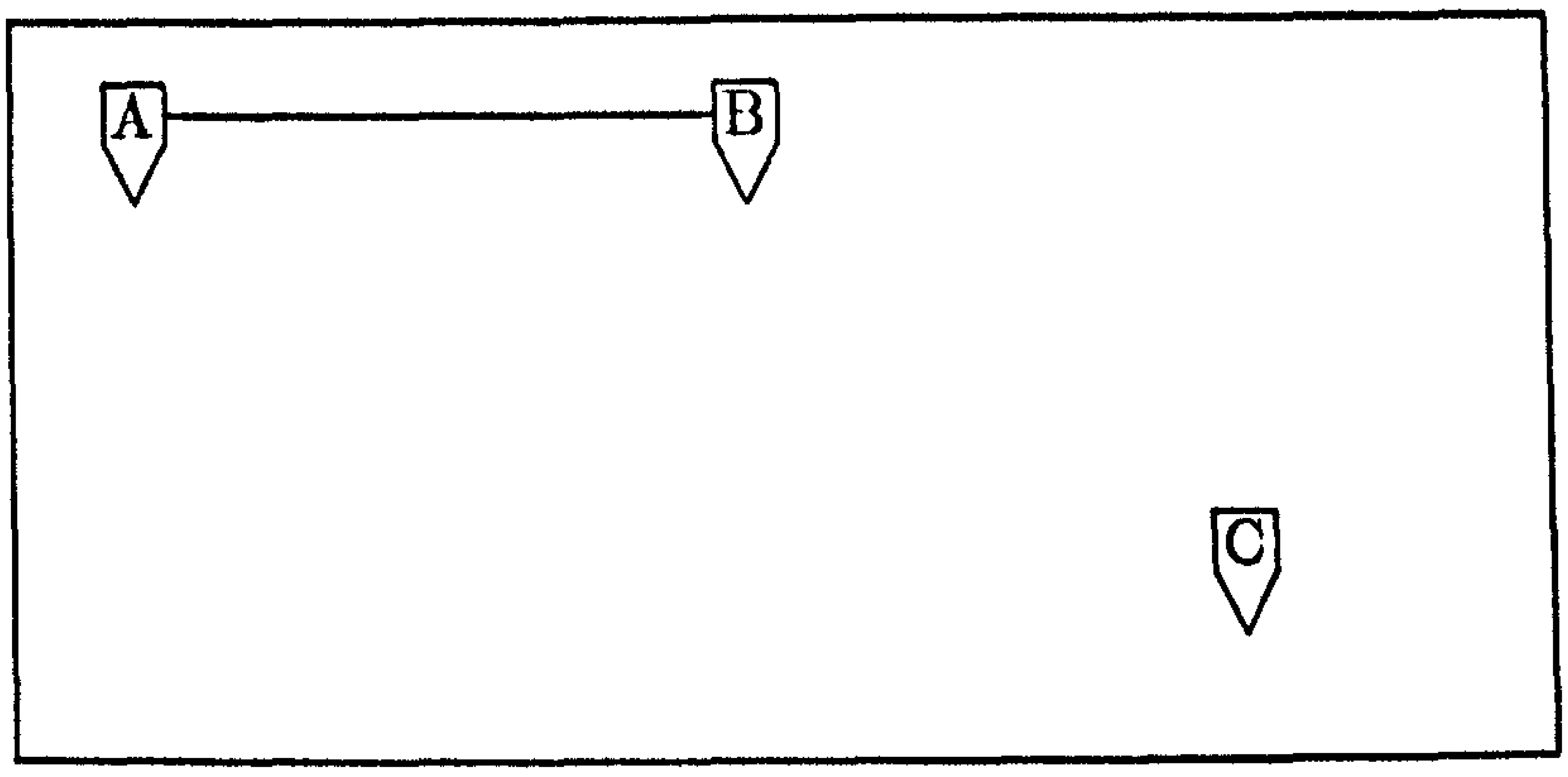


Figure 4–12: DYNLAB: Question 5

This question (see figure 4–12) is also extracted from the same paper by Clement [Clement 82]. His results indicated some interesting variants. Perhaps the most interesting is the path that goes in a straight line from B to C and then in a straight line from C parallel to AB. Prior to a mechanics course some 40% appeared to hold this belief.

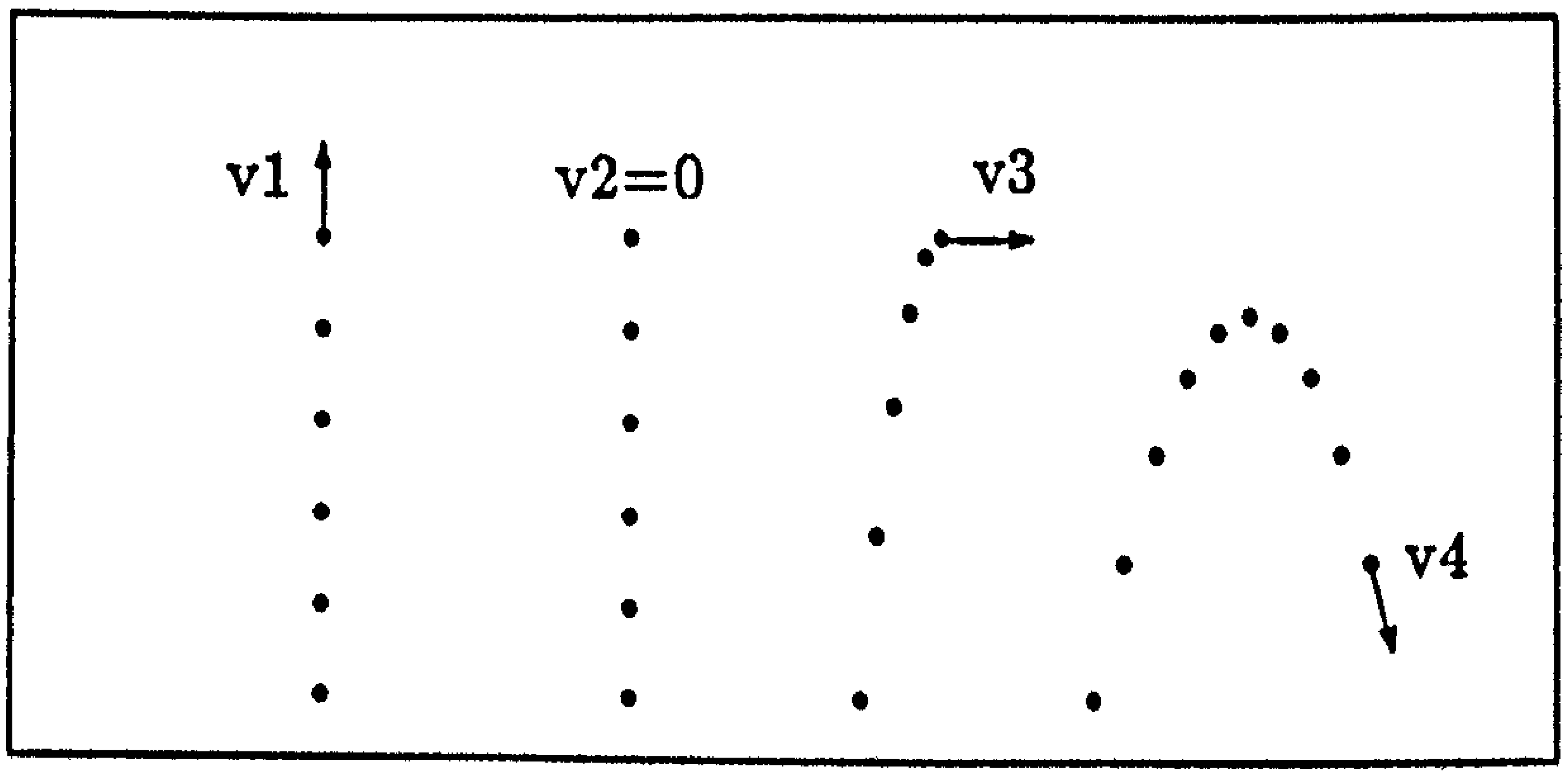
For the first part of the path, five students were correct in drawing a curved path while three drew the path from B to C in a straight line —in accord with an impulse rather than a sustained force. The remaining two are quite interesting: one produced something reminiscent of the *Aristotelian Corner* strategy in that the rocket was sent in the direction of the force while the other produced a solution in which the rocket started to go at right angles to AB and then gradually resumed its previous direction!

The second part of the path was acceptable for seven answers. Of the remainder, two made the rocket suddenly continue the direction of the path that it had before its motors fired and the third gradually took up the path the rocket had previously followed.

On the whole these results are more typical of Clement's results for the students at the end of their mechanics course. This is plausible since all the students had recently sat their Physics 'O' grade examination.

Question 6

6. A juggler throws four balls in the air.



The arrows indicate both the magnitude and direction of the velocities of the balls.

Are the forces acting on the bodies identical? —Answer Yes or No

Give a reason for your answer.

Figure 4-13: DYNLAB: Question 6

This question (figure 4–13) was extracted from a paper by Viennot [Viennot 79]. The results obtained indicated that the students often said that the forces were unequal.

This was, in many ways, the least satisfactory of the ten questions in that the phrasing permits the student to interpret the word "are" as referring to the whole history of the balls. Of the ten answers it is not easy to say which are correct. Nevertheless, the reasons offered were illuminating.

- Each ball is travelling in a different direction therefore they have different forces acting on them

- No, because the juggler is throwing the balls up at different speeds and in different directions

- The third and fourth balls are drawn back to the ground by gravity but this does not affect the first or second balls

- ..but ball 1 has a force pulling it upward whilst ball 2 has no force pulling on it

The question was supposed to be about the forces acting at the instant at which the bodies have the indicated velocities. The phrase which would have made the question more precise was omitted by accident. There is, however, a strong similarity between the explanations given above and the responses outlined by Viennot. Viennot's students either simply ignored this condition or it has a deeper significance in that students automatically offer explanations based on the history of the particle.

Question 7

This question (see figure 4–14) was an attempt to see whether any of the results of Caramazza, McCloskey and Green could be obtained [Caramazza et al 81]. Unfortunately, DYNLAB cannot be used to model such complex motion so this question was chosen as a poor substitute.

7. An ice cube slides along a smooth table and falls off the end moving fast.

On the diagram, indicate the path that the cube takes.

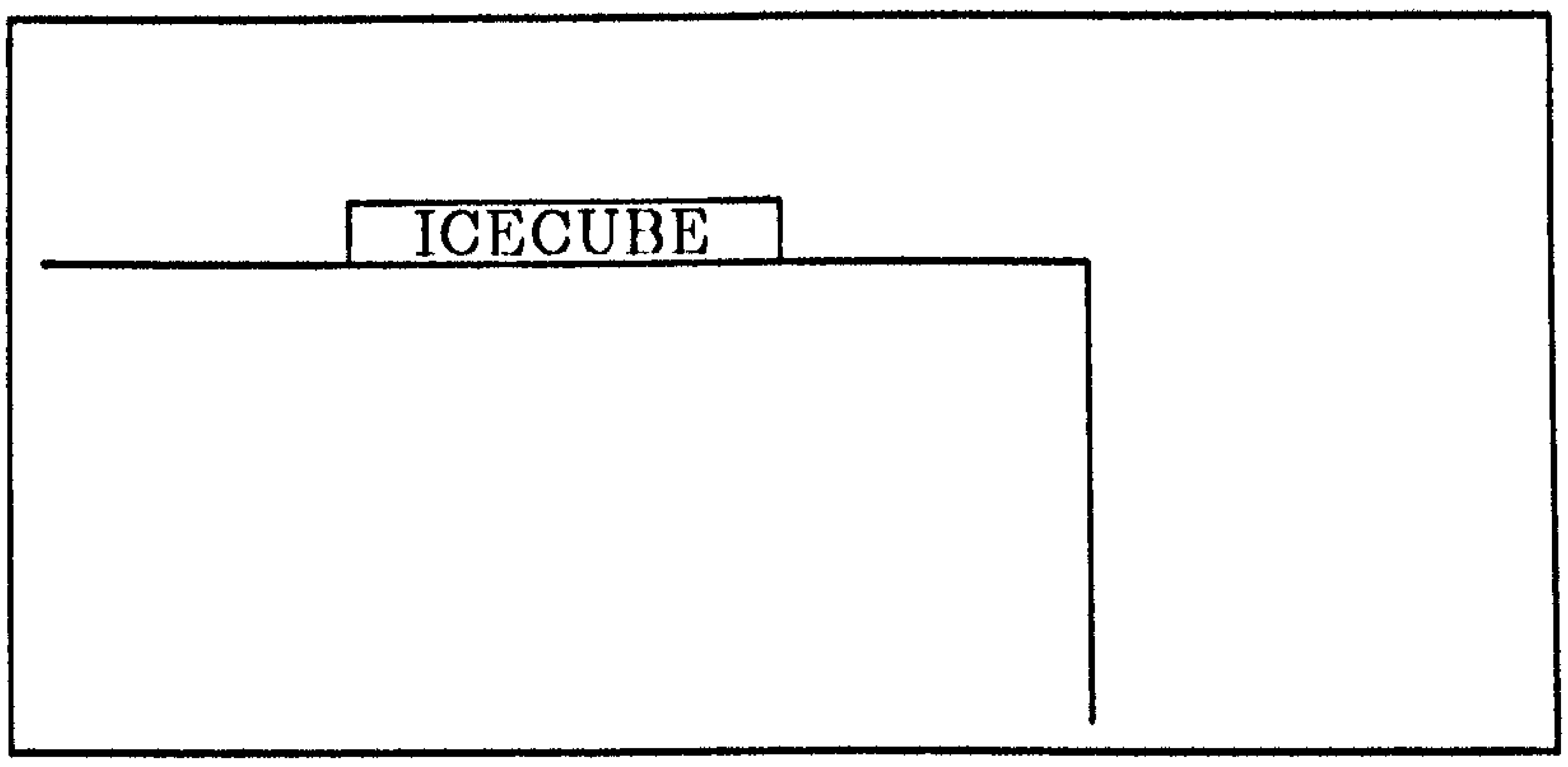


Figure 4–14: DYNLAB: Question 7

All the students answered correctly but it is interesting to note, in the light of the article by McCloskey [McCloskey et al 80] that every one of them produced a path that looked remarkably circular rather than the required parabola. This might simply be because it is accepted that if you want to draw a curved path then you can draw an arc of some circle. On the other hand, one of the students who later modelled this situation using DYNLAB stated that he was surprised by the shape of the path obtained with DYNLAB.

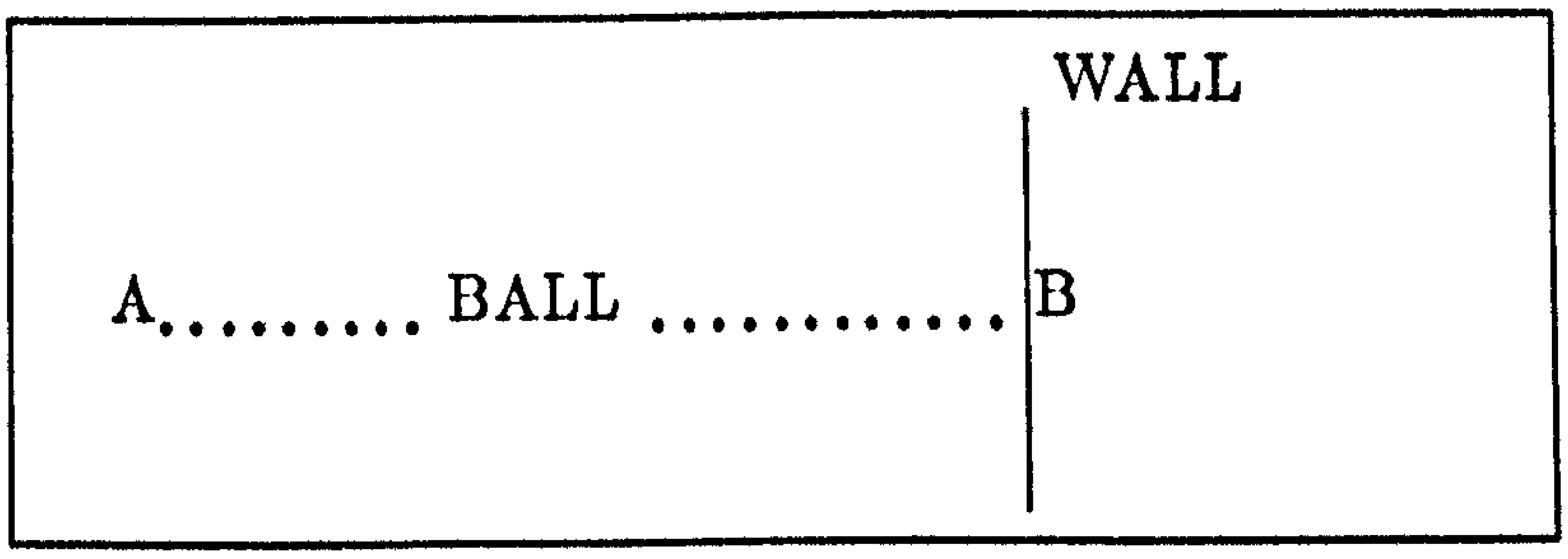
Question 8

The design of this question (see figure 4–15) was prompted by a suspicion that students are not good at distinguishing distance-time graphs from displacement-time graphs. Some research indicates that younger children can confuse the actual path of the object with the graph itself [Avons et al 81b].

For the first part, eight were correct and the other two produced some variation of distance-time graph.

8. A ball moves from A along a smooth table and hits a vertical wall at B.

The ball bounces back along the way it came.



Sketch

a) The displacement-time graph

b) The velocity-time graph

Figure 4–15: DYNLAB: Question 8

For the second part, six were correct, two produced graphs of the magnitude of velocity against time and one produced what appeared to be a displacement-time graph having produced a distance-time graph for the first part. Only one person actually produced a graph with time *flowing backward.*

Question 9

This question (figure 4–16) was a modification of the Speed Comparison Test 1 found in a paper by Trowbridge and McDermott in which it was observed that quite a large percentage of students identified the places at which one object passed the other with the places at which the bodies have the same velocity [Trowbridge & McDermott 80].

There were three correct answers —marking the place as at the time of the fourth strobe flash. Four students produced answers identifying passing with equal velocity of which two only identified one of the two passing places. Of the remaining three, one seemed to think that they both started with the

9. Ball A rolls along the ground at a steady speed while ball B rolls up a plank.

The following diagram indicates the result of a series of strobe pictures taken from above.

On the diagram, indicate where you think the balls have the same velocity.

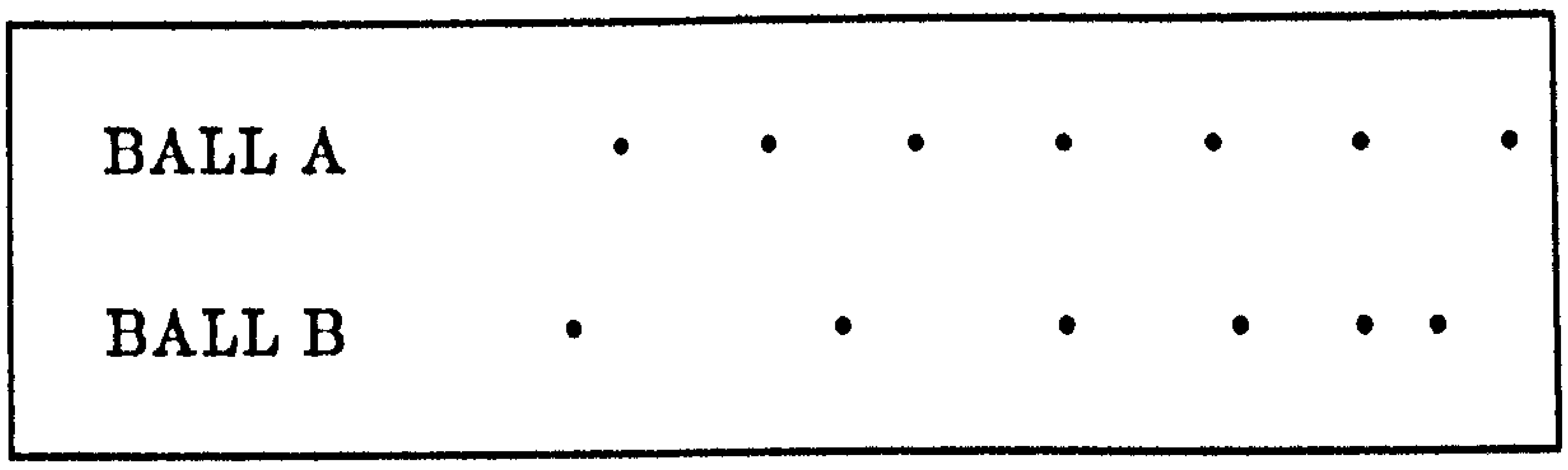


Figure 4–16: DYNLAB: Question 9

same velocity and the other two were difficult to assess but may well have been inaccurate attempts to apply a correct procedure.

Question 10

Figure 4–17 was taken from another paper by Trowbridge and McDermott in which it was found that there were a number of confusions of velocity for acceleration [Trowbridge & McDermott 81]. The question is their Acceleration Comparison Task 2.

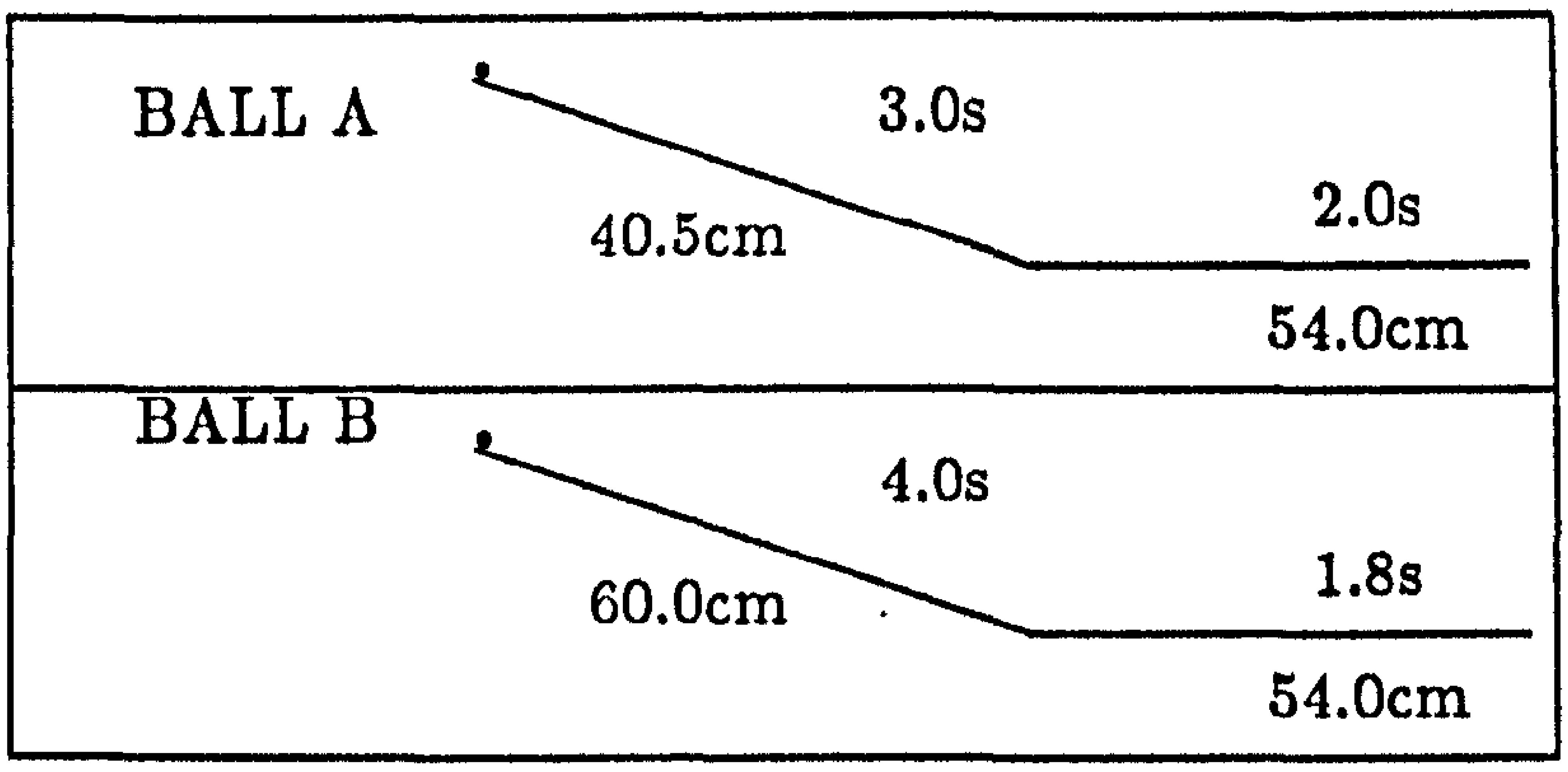
Six students answered this one correctly by choosing ball A. Of the remainder, three made mistakes in assuming that a greater velocity implied a greater acceleration and one assumed that

> as ball B has a greater distance where it can accelerate due to gravity
> it must have the greater acceleration

10. Two balls rolled down sloping sections of track (not necessarily the same slope) and onto level sections where they have uniform motion.

Times and distances are measured and shown on the diagram.

Answer the following question showing all your working. NO credit will be given for answers which use the formula $s = ut + 1/2at^2$.



Which ball had the greater acceleration?

Figure 4–17: DYNLAB: Question 10

—a perfectly plausible line of reasoning but disastrously wrong in that the student ignored the comment about the difference in the slopes and failed to see that the numerical evidence contradicted his answer.

4.5.4 The Observations

Five situations of the ten were provided with guidance that was distinctly less specific than that provided by previous worksheets. These situations were placed in order of estimated difficulty:

ONE	EIGHT	THREE	SEVEN	FIVE

The final results seemed to indicate that EIGHT was easier than ONE although this may have been due to increased familiarity with the system.

An Overview

The table 4–1 gives some idea of how quickly the students went through the modelling process. Each row indicates the number of students who finished the given modelling situation. One student, however, only spent two periods of forty minutes on the work compared with three for the rest. The arithmetic mean is

Finished	Number
1st	10
2nd	9
3rd	3
4th	2
5th	1

Table 4–1: Completion Figures

roughly 46.5 minutes. Although it is not possible to do any worthwhile statistical analysis on the results it is interesting to note that the Spearman's rank correlation for the number of questions answered correctly in the test against the number of situations modelled was approximately 0.8 for the nine who each had two hours of building. There is also likely to be a strong correlation between other variables such as typing speed and number of situations modelled etc.

At this point it becomes easy to adopt the view that everything is loaded against the 'average' student in this sample. S/he has a significant number of misconceptions, s/he is not good at typing, and s/he is not an experienced computer user. Is this a case of *to him that hath let it be given*?

More Detail

The situation ONE is of most interest in that everyone modelled it. EIGHT is another contender since all but one modelled it. As it produced far less confusion, EIGHT is of much less interest. Indeed, in retrospect, it is not surprising that

EIGHT has less appeal since the misconceptions were likely to appear in the interpretation of the graphs rather than in the modelling of the situation.

Initially, it seems reasonable to split the problems that students encountered into three types:

- Trouble with the Diagram
- Trouble defining the Object
- Trouble impelling the Object

Trouble with the Diagram A number of different diagrams were constructed which basically fell into three categories: standard, simplified and incorrect.

The Standard Diagram Figure 4–18 shows the basic standard diagram as used by four of the students who, for convenience, will be known as students A, B, C and D: The ball is to start from A and travel to B where it receives a kick

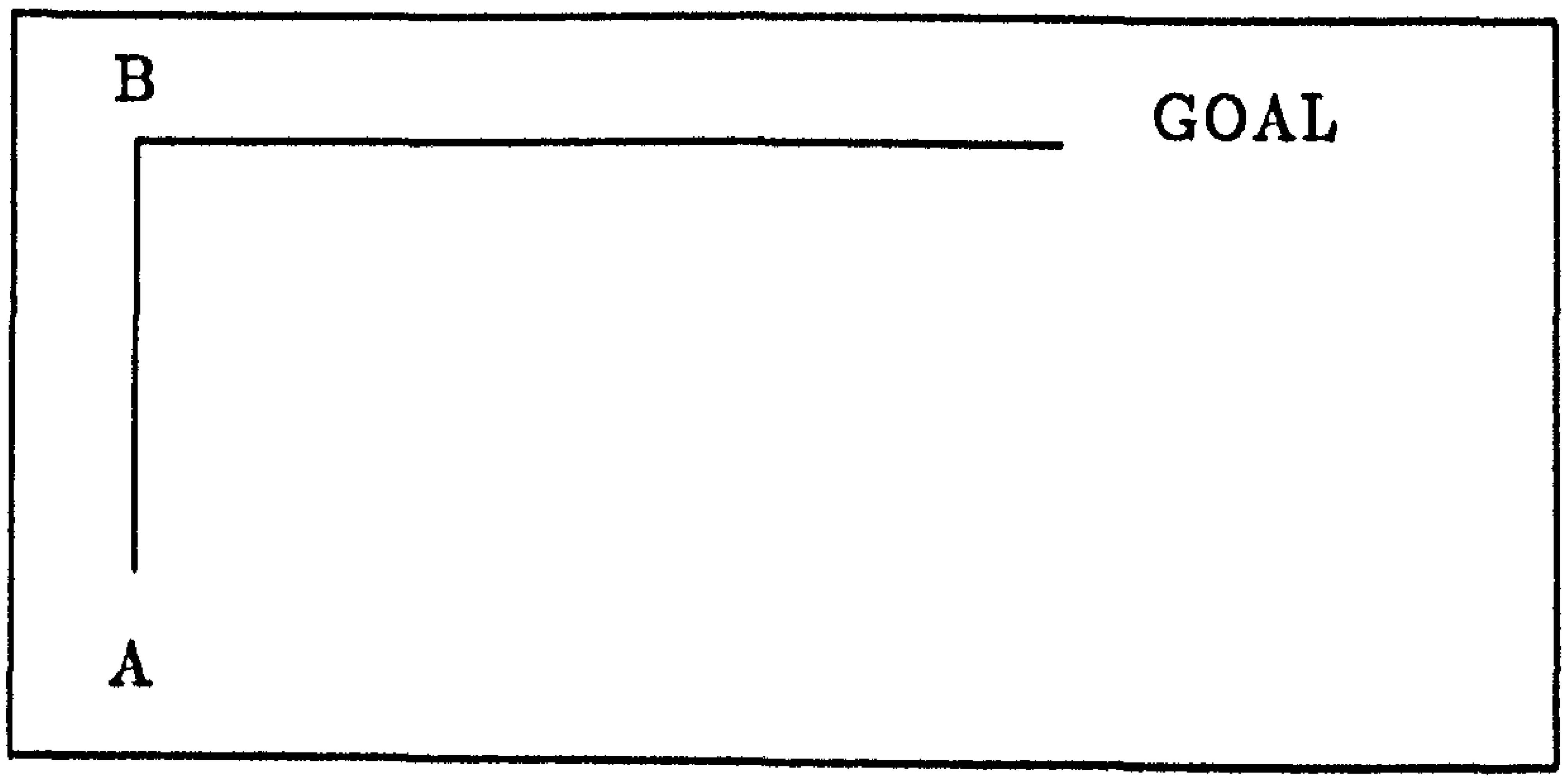


Figure 4–18: The Standard Diagram

in some direction. Two students started the ball at a place called BALL —no doubt inspired by the original diagram in the question. This occasionally created some confusion as to whether they were referring to the place called BALL or the ball itself. Giving students the ability to name things for themselves can here be seen to carry the possibility that they will confuse themselves by not making good type distinctions in their own minds. On the other hand, it is the detection of the inability of the student to distinguish between types of entity which may be of interest to the physics teacher.

The Simplified Diagram This appears in two distinct versions. The first version, shown in figure 4-19, involves imagining the GOAL and was adopted initially by three students of the ten —students E, F and G. The three students

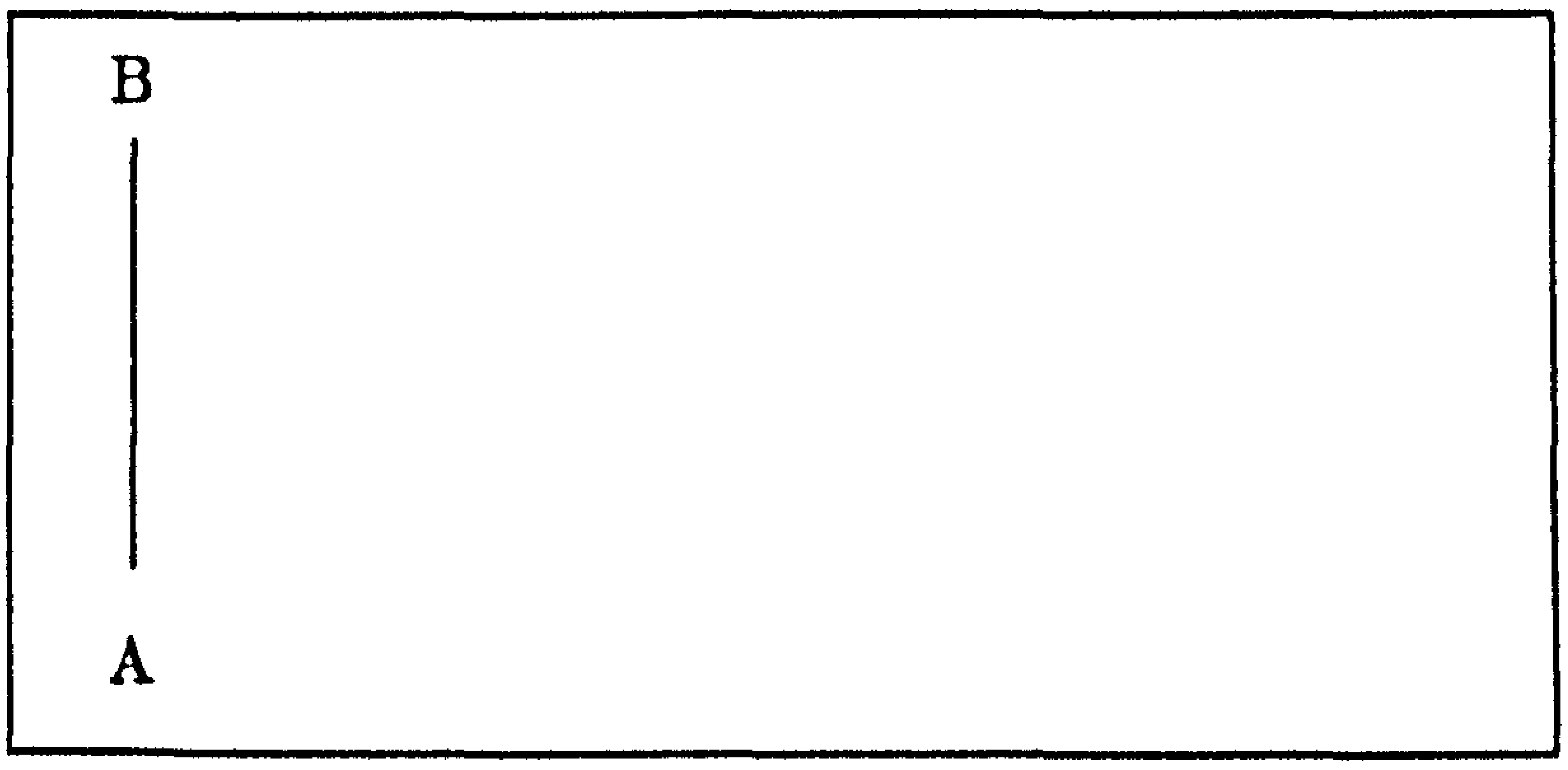


Figure 4–19: Simplification: Version 1

showed some evidence that they were visualising the GOAL in the standard place. A fourth student, student H, constructed a different version (see figure 4–20). This diagram suggests that the student might have seen the AB stretch as

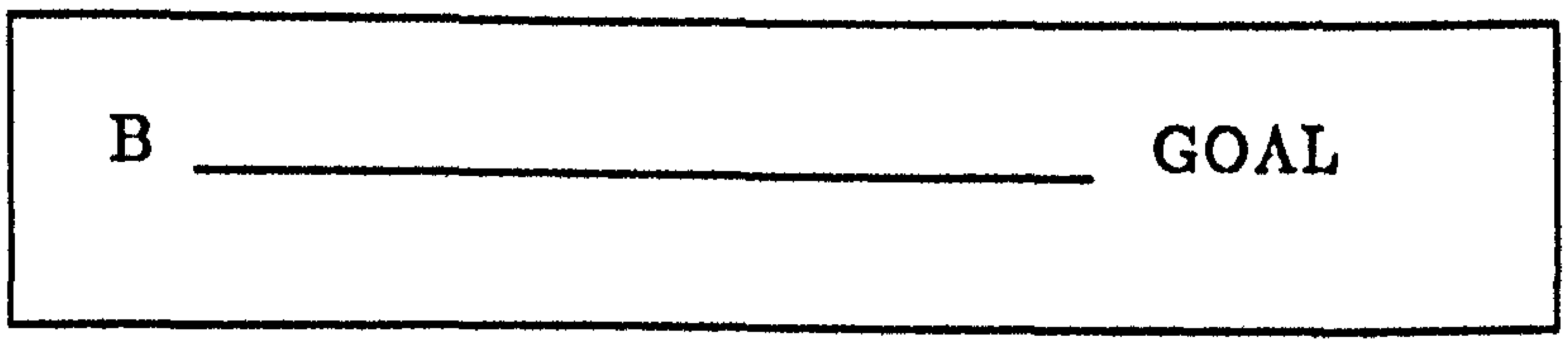


Figure 4–20: Simplification: Version 2

redundant. He is about to give an initial velocity to the ball at B and a kick at B at the same time —a perfectly reasonable approach. Student H who adopted this diagram did not seem to have this in mind as he simply kicked the ball from rest at B toward the GOAL. In other words, he had not comprehended the basic problem. Here, the simplified diagram is a reflection of the student's belief that the motion prior to B is irrelevant or non-existent.

Incorrect Diagrams The remaining two students produced incorrect diagrams although one of them, student I, seemed to have been wrong by virtue of an arithmetic slip rather than any misconception about the problem itself. Student I attempted to transform the basic diagram/problem into quite an exotic version —as shown in figure 4–21. His failure was to calculate the bearing

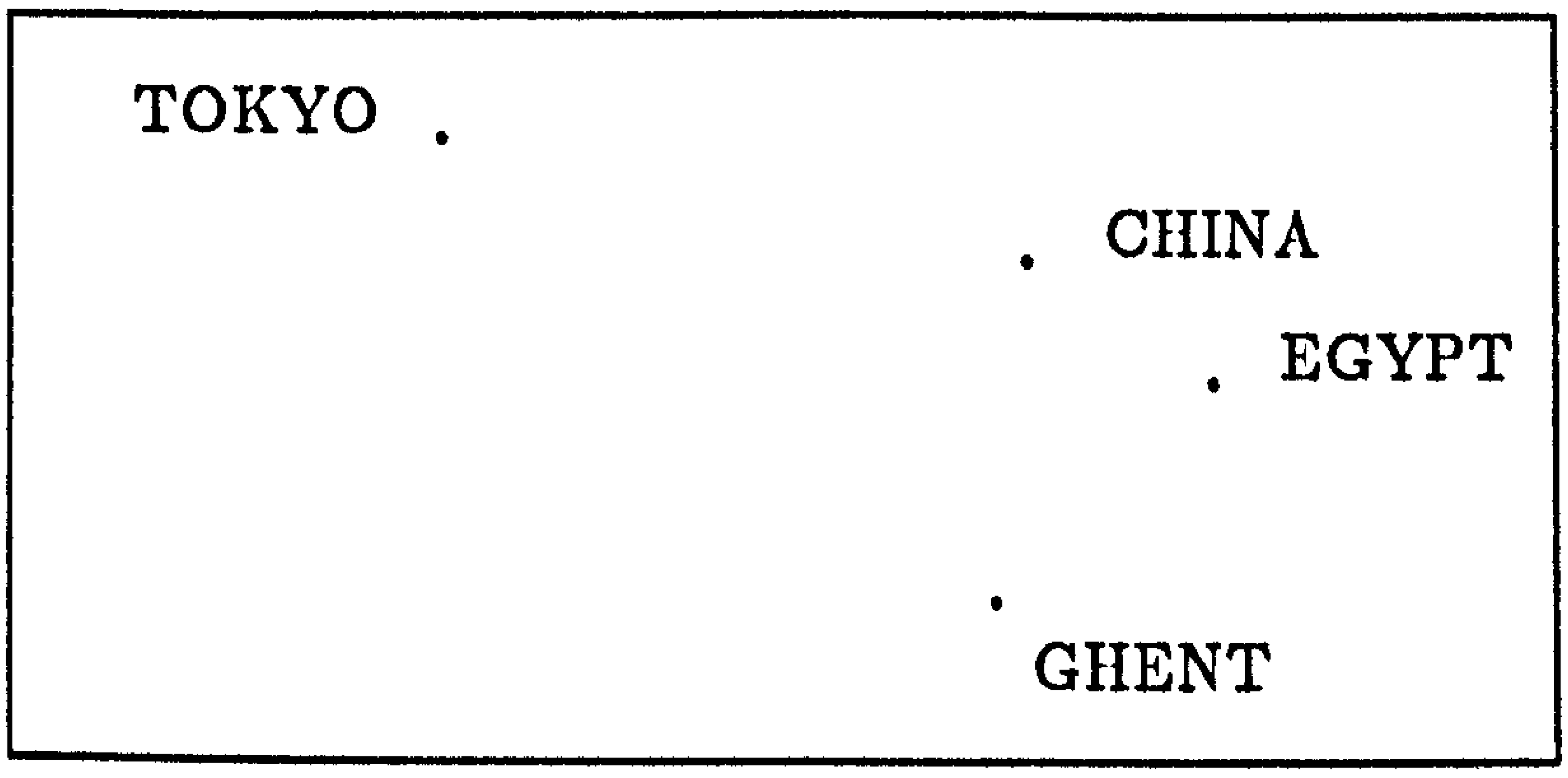


Figure 4–21: Student I's Diagram

from GHENT to EGYPT correctly. CHINA to EGYPT is his model of the GOALmouth.

The final student, student J, produced a diagram showing a poor grasp of the original problem (see figure 4–22). Apart from any other problems that he had with this situation, he seemed to perceive the problem as a beginning and an end but with no clear middle. That is, he appreciated from where the ball started and where the ball had to end up but he seemed to have little grasp of the process that was to take place in between.

Trouble with the Object There were few problems associated with the definition of the object. A minor problem occurred in that several students failed to note that it was necessary to say where the ball was to start. It is difficult

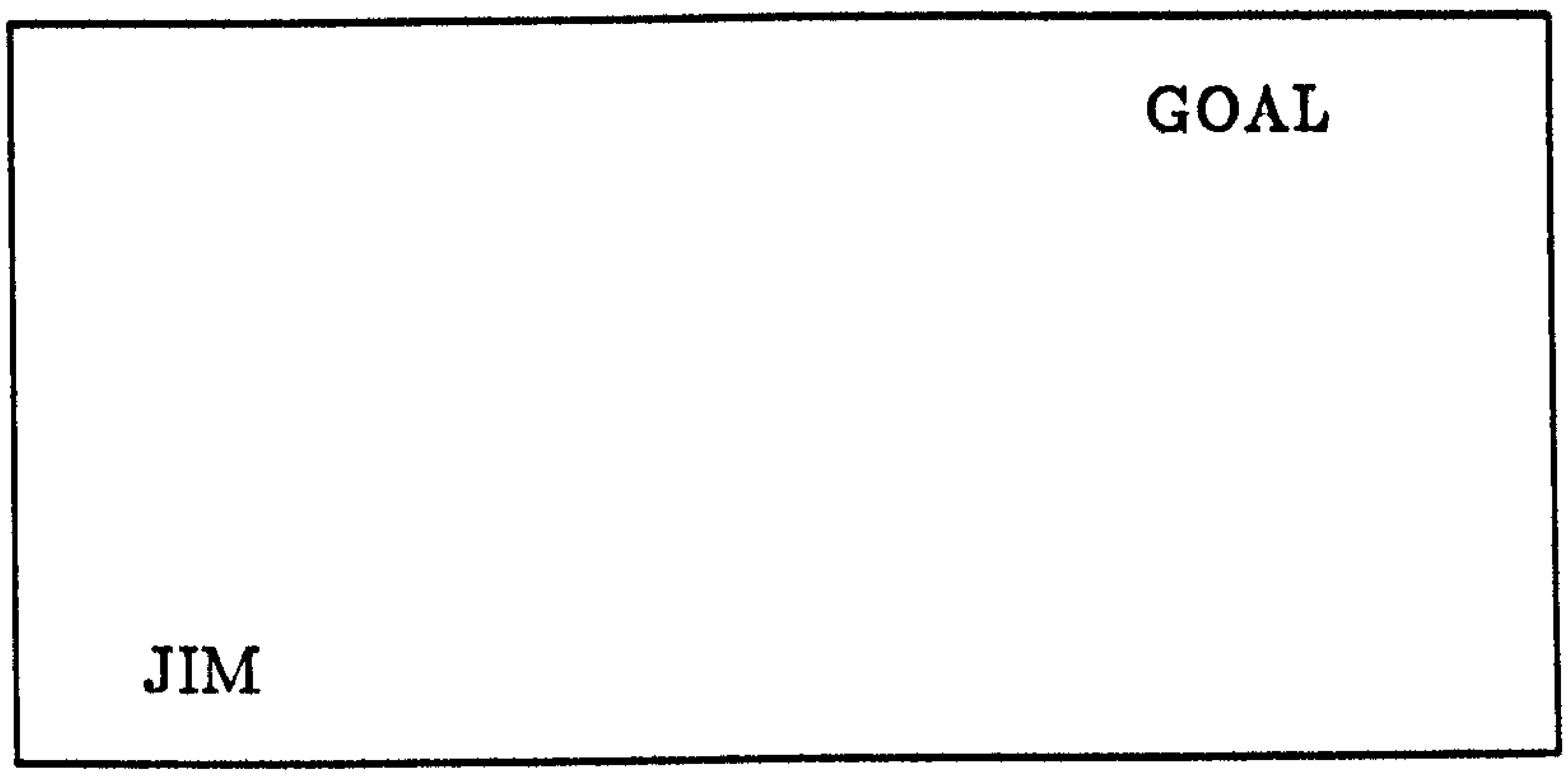


Figure 4–22: Student J's Diagram

to explain this unless they felt that in defining a velocity they were implicitly specifying the start location.

Eight of the ten had no difficulty defining the initial velocity. Student J who had an incorrect diagram and an incorrect perception of the problem failed to give the ball any initial velocity at all. The remaining student was student H who produced a simplified diagram. He gave the ball an initial velocity directly toward the GOAL!

Trouble with Impelling the Object Only two of the ten produced a satisfactory solution. Initially, the first of these, student A, appeared to apply the *Aristotle Corner* strategy previously described despite a correct answer in the test. It turned out, however, that his initial KICK perpendicular to the direction of the ball was in the nature of ranging shot as he quickly rotated the direction of the KICK in a sensible manner to produce a solution.

The next satisfactory solution came from student E after an initial arithmetic slip about the bearing. He quickly corrected the mistake and tried a backwards and sideways KICK. As this did not work exactly, he resorted to a ranging shot perpendicular to the path of the ball followed by a sensible rotation of the KICK.

It might be worth looking in slightly more detail at student E's attempt. He gave the ball an initial velocity of 2m/s on a bearing of 0 degrees. His KICK was 2Ns on a bearing of 135 degrees. He made no attempt whatsoever to reason out that his KICK had too large a magnitude.

Of the other eight students, two more produced fairly straightforward versions of the *Aristotle Corner* strategy. The first of these, student F, tried the perpendicular KICK and then, confusingly, added a perpendicular KICK in the other direction! Eventually, he discarded one of the KICKs but clearly showed some failure to recall where the GOAL was as his diagram was one of the simplified ones not showing the GOAL. Eventually, he rotated the KICK until he obtained a satisfactory solution.

The second, student B, produced a couple of interesting variations. He tried the basic *Aristotle Corner* strategy and then increased the size of the KICK. Despite the slight improvement in the result, he was unhappy. He decided to slow the ball down by reducing both the mass —by a factor of 100— and the KICK —by a factor of 10. It is possible but by no means certain that he was trying to reduce both quantities by the same amount. Again, he was not satisfied with the result. After some time, inspiration struck quite evidently —he decided to change the direction of the KICK. He tried a fairly sensible direction but the result was still far from that required. He increased the direction of the KICK in the obvious way but in such a manner that the KICK was now diametrically opposed to the direction of the ball. He did not seem to see why this was such a bad choice. He reasoned from this that he should go back to the perpendicular KICK but he was aware that this would not work out so he again rotated the KICK, changing the magnitude of the KICK simultaneously. Thus, he showed little practical awareness of the need to change one variable at a time.

Inevitably, when students are confronted with such an open ended problem there will be those who have not reached sufficient intellectual maturity to try to change one variable at a time. One may therefore propose that DYNLAB gives the diligent teacher an opportunity to focus on this problem with a possibility of success. Further, one may also ask why the student cannot learn the same lessons from a laboratory situation. Perhaps the answer is that he can but the computer certainly offers a quick way of doing the same thing. Another question to ask concerns the actual opportunities given to the student to help him/her come to terms with this problem —it is suspected that too often most experiments are presented in such a way that the student has only one obvious variable to change.

Student H produced a simplified diagram as shown in figure 4–23. He applied

Figure 4–23: Student H's Diagram

a FORCE rather than a KICK and 'succeeded' rather easily. He had given the ball no initial velocity which meant that it had a velocity of zero by default. After a little prompting, he saw that he had not modelled the problem correctly. He gave the ball a sensible initial velocity and applied a FORCE perpendicular to the direction of the ball. He was evidently very confused about the difference in nature between a FORCE and a KICK. It is also worth noting that this student answered the test question correctly indicating that his exam training was papering over some deep cracks in his understanding.

All the other five included both a continuous FORCE and a KICK at some stage in their attempt to solve the problem presented. One of the clearest attempts involved a FORCE moving the ball up the screen and a KICK in roughly the correct direction —backwards and sideways. Student C who tried this model played around with different magnitudes for the KICK but eventually discarded the FORCE completely. After a few adjustments to the magnitude of the KICK and a small rotation he solved the problem. Nevertheless, initially he seemed to be trying to keep the ball moving with some force acting on the ball —possibly to overcome friction?

Student D produced an interesting strategy. But first, he had some problems interpreting a KICK at a place as a KICK towards the place. Also, he seemed to be very confused about the nature of impulse. First, he used both a FORCE and a KICK then removed the FORCE. He started to apply the *Aristotle Corner* strategy but before he saw the result he realised that he had made a mistake. He then came up with the idea of two KICKS applied to the ball at the same place — one to bring the ball to rest and the other to take it to the final target. He was the only student to produce this strategy. He also exhibited a way of thinking about the situation that showed that he made little attempt to distinguish different kinds of abstract entity. For example, in reasoning about the magnitude of the KICK needed to bring the ball to rest, "A force of 10 up (he means a velocity of 10m/s) and then a force of 10 at JIM stopping it (an impulse of 10Ns) and then a force of 10 to GOAL (an impulse of 10Ns)".

Only one student, student G, tried to apply both a FORCE and a KICK perpendicular to the path of the ball. The FORCE, however, carried the ball on a curved path thus missing the place where the ball was to receive a KICK. He changed both the mass of the ball and the initial velocity but he was unhappy about the force. Was he about to discard it? No, he wanted to switch the FORCE on once the ball reached the place it was to receive the KICK. After he was shown how to do this, he tinkered with the direction of the FORCE. As the ball moved on a curved path and as he was one of those who used the simplified diagram missing out the GOAL he had some difficulty deciding if he had solved his problem. In an expedient manner, he simply positioned his GOAL so that it lay on the ball's path. When asked whether his result was one that would be observed in real life he hesitated and then very positively said that he was sure that his result would be observed in real life. The question to ask here is whether there is any basis for such an opinion. It is conceivable that there might be. Imagine a footballer running at a steady velocity from A to B and beyond. As he reaches B he boots the ball towards the GOAL and, because of the effects of friction, he sees the ball gradually losing its component of velocity in the direction in which he is running. From his point of view, he sees the ball curving backwards!

Finally, we have the two students who produced incorrect diagrams. Stu-

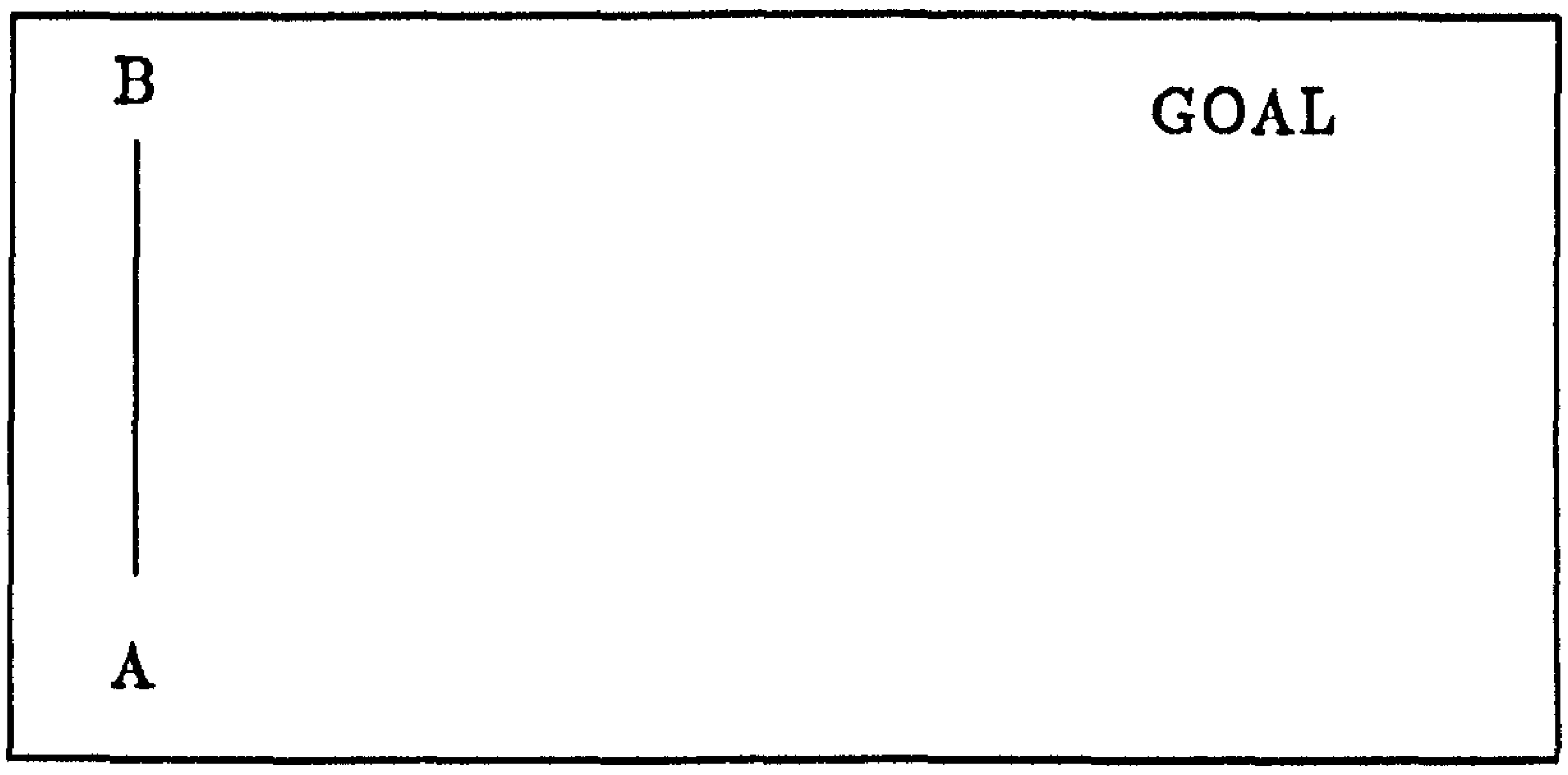


Figure 4–24: Student G's Diagram

dent I who produced an almost correct transformation of the problem tried to apply both a FORCE and a KICK. There was no obvious attempt to use the *Aristotle Corner* strategy and, in a while, he dropped the FORCE completely. After changing the direction of the KICK, he was successful. Again, it is worth noting that the test result indicated that this student was likely to try the *Aristotle Corner* strategy which, in practice, he did not —perhaps more by good luck than judgement since the (slightly incorrect) transformation of the problem did not produce the need to turn the ball through a right angle.

The final student, student J, used both a KICK and a FORCE aimed initially either side of the target. He then took a long time to produce a solution for the ball starting from rest. He failed to apply the idea of altering one variable at a time. After an intervention to give the ball an appropriate initial direction, he tried an erratic set of directions for the KICK showing little awareness that a small change to the situation generally produces a small effect. Again, he seems satisfied with a curved path.

A Summary of the Impulsion Attempts Several students made some use of the *Aristotle Corner* strategy and seemed deeply committed to it. Only one student saw that it was possible to apply two KICKs at one place to produce a combination equivalent to one KICK. Several students seemed to be unaware of the difficulties met if they changed more than one variable at a time. The acceptance by several students of a curved path for the ball suggests that there may be a strong influence from the perception of the way things work in the real world which interferes with the simpler model that ignores friction.

The Other Situations

The time allowed for observations did not permit students to complete the tasks set them. Only one very able student actually completed the modelling of all five test situations. By far the largest time was spent on situations named ONE and EIGHT. Despite this some interesting comments can still be made about situations named THREE, SEVEN and FIVE.

EIGHT Student C had no problems writing the program at all. It was the interpretation of the magnitude of velocity-time graph that caused him any difficulty. He wanted to know why this did not go negative. The explanation is that the magnitude of the velocity is always a positive quantity. Taken in conjunction with his test result this suggested that he had a clear understanding of the taught concept of a velocity-time graph. On the other hand, student I answered the test question as if the question had asked for a speed-time graph and was not at all worried that DYNLAB had produced a graph that looked the same and called it a magnitude of velocity-time graph.

One problem exposed by this question is what the user means by some such command as:

```
KICK BOUNCE B 10 NS 270
```

which is 'pretty printed' by the system as:

```
KICK (name) BOUNCE (at) B
     (of) 10 Ns (in direction) 270
```

If this KICK happens to stop the object kicked dead in its tracks then the object will still be at B and hence the subject of a further KICK! There is a double kick. In other words, the user has to see that a KICK statement sets up a kind of daemon which will apply the KICK whenever the relevant object is found at a certain place. This is perfectly reasonable but student I did not notice the double kick. He intended the kick to reverse the motion and that is what happened. The trace makes it clear what happened but there may be a need to indicate the activation of KICKs and FORCEs in a more obvious way.

Student G added a force that accelerated the ball only until it reached the wall. He took some time to realise that the kick he gave had slowed up the object kicked but he was surprised when it was suggested that this object had been accelerating. To solve the problem he did not remove the accelerating force —just increased the KICK. The graphs were interpreted satisfactorily despite his inability to correctly generate either of the required graphs during the test. His program is shown in pretty printed format in figure 4–25.

```
MAP
DISPLACEMENT (from) A (to) B
    (of) 10m (in direction) 90
JOURNEY BALL
START (at) A
VELOCITY (at) A
    (of) 1m/s (in direction) 90
FORCE BOUNCE
FORCE (name) THERE
    (of) 1N (in direction) 90
    (until magnitude of)
    DISPLACEMENT (is) 10m
ACTS (on) BALL
KICK (name) BACK (at) B
    (of) 5Ns (in direction) 270
```

Figure 4–25: Student G's First Attempt at EIGHT

Only two students indicated an awareness that the object should not return faster than it started. Student D quite explicitly arranged for the object to return at a slower speed.

THREE Student E decided to switch gravity on. This meant modelling the force of the ground upon the man and a similar reaction force on the ball which lasts until a KICK is given vertically upwards. Initially he tried to bundle both the forces on the man and the forces on the ball into the same FORCE. This suggests a confusion about the scope of the ACTS command in that he thought of a FORCE as something like:

ACTS BALL
<FORCEs and KICKs applying to BALL>
ACTS MAN
<FORCEs and KICKs applying to MAN>

Once he realised that this did not produce the desired result he separated the FORCE into two FORCEs by first modelling the FORCE and KICK on the ball and then the FORCE on the man.

Student A switched gravity on and modelled the reaction of the ground on the man implicitly assuming that g was $10m/s^2$. After noticing the man rising upwards he tried to correct by increasing the reaction. He finally modelled the situation correctly and managed to answer the basic question by observing that the ball was always vertically above the man.

Student C did not model a constant force due to gravity acting on both the man and ball. This lead him to need to turn on gravity for the ball at the same time as the ball is kicked. He had some difficulty in realising the sequential nature of the FORCE commands but he solved the problem by putting in a dummy force of 0N acting on the ball until the kick when the force changed to represent the unbalanced set of forces upon the ball. After modelling the situation correctly he could not decide whether the ball landed exactly on top of the man. He ended up defining a new position where he thought the two bodies might meet and tried to kill the ball's velocity using data from DYNLAB's printout. The result may have satisfied the student but he did not choose too reliable a strategy.

SEVEN and FIVE Only students E and A managed to find time to model situation SEVEN. Student A initially put the reaction force of the table on the icecube in as 90 degrees which puzzled him for a while. He then produced a good solution. Student E had no problems at all with either situation.

4.6 Some Conclusions

It is now time to consider what principles and problems have emerged from the design and use of DYNLAB. For convenience, these comments are stated in terms of the three strands of interest woven through the thesis: Modelling Environments, Misconceptions and Educational Issues. Inevitably, a completely clean compartmentalisation is impossible.

4.6.1 DYNLAB and some Educational Issues

Most of the effort during the observational period went into examing the progress of individuals as they attempted to solve a number of problems. However, learning rarely takes place in an isolated environment and consequently something of the wider aspects of the educational environment needs to be considered.

Training Students to Use DYNLAB

It might be thought that students should first learn a computer language and then apply this knowledge to various problems. For example, in a study of the teaching of Mathematical ideas through LOGO programming, students were taught LOGO during the period of a school year and then taught mathematics using LOGO in the following year [Howe et al 82]. This presupposes that one can separate the learning of the programming skills and concepts from the domain in which the language is to be applied. In the case of computationally sophisticated modelling environments which represent the *real* world in some way then it becomes harder to 'teach the system' before the students use it to learn more about the domain.

The strategy adopted in practice required the students to learn more about DYNLAB in parallel with exploring simple and reasonably familiar aspects of dynamics and kinematics. This lead to the construction of the large number of worksheets outlined in section 4.4.6. Although the first six worksheets are described as *introductory* it was never supposed that the students would be able to learn all about DYNLAB within the space of about two lesson periods.

The belief is that the students made extensive use of the worksheets. In general, there were few problems in using the worksheets although it is more difficult to be certain as to the extent of their understanding of the tasks given them. The impression was that most of the time most students knew what was wanted of them.

Where DYNLAB Fits into the Classroom

DYNLAB is not designed as a substitute for a physics laboratory —it is a different kind of laboratory. Unlike ROCKET, DYNLAB has a place in the ordinary physics curriculum in that many simple activities can be undertaken that may be used to reinforce existing concepts or teach new ones —in addition to the exploration of physics misconceptions. This can only be good because physics teaching certainly consists of more than *debugging mental models.* Any future, more sophisticated, version of DYNLAB should continue to meet the multiple requirements of the practicing physics teacher.

The current version of DYNLAB would seem to be most useful for those students who have some ideas —formal or informal— about concepts such as mass, impulse, displacement, velocity and so on. Because the targetted students have often met the ideas before it seems quite practicable to use DYNLAB as an introduction to new work, an alternative to selected laboratory experiments or remedial work.

On the other hand, the attempt to use DYNLAB to clarify the conflict between velocity and speed (and similar problems) does not easily fit into current curricula. The results of the observation period tended to confirm that students often make rational mistakes based on the failure to distinguish between velocity, speed and the magnitude of velocity.

Training Teachers

An improved version of DYNLAB was left in the physics department but, on going back sometime later, the impression was gathered that the program had not been used. This might have been practical criticism of the whole venture but there are some other important factors.

Throughout the observational period teachers expressed interest but manifestly had not sufficient time to be educated about the system.

One program that the physics department did use had a single function — involving the use of the computer as a timing device in the measurement of acceleration. This suggests that one factor might be the ability to treat a program as a black box enabling the teacher to save time. Complex systems cannot be so treated. Such systems must be applicable in different ways and at different places in the curriculum if the extra time needed to learn them is justifiable.

Learning a complex system is difficult when the teaching profession is under great stress to create new educational courses and develop new evaluation methods. If systems like DYNLAB are to be used effectively then teachers need special in-service training periods. These training periods are not just explanations about how to use the system but on how both to teach and how to help students learn to use the system.

4.6.2 DYNLAB as a Modelling Environment

The construction of DYNLAB is an experiment in building a *sufficiently* powerful environment to explore a specific range of problems. Much about it could be improved in order that the system becomes more user-friendly and more flexible.

The User Interface

Throughout the system, the user communicates through a simple command interpreter. Inevitably, with long commands to type in, there is a strong requirement on the user to become familiar with the syntax —however baroque. For this reason a command summary sheet was made available along with the system documentation. Some students found the complexities of the syntax difficult to handle but the overall judgement is that it caused surprisingly few problems. Some students had difficulty with spelling words like *displacement.* To partially account for this it was observed that the students often consulted the command summary.

The most interesting errors, however, were those of omission. Students would forget to specify which object was to be changed while talking to the Situation Interactor. It is as if they assumed that the system would have enough intelligence to know which object they were referencing. In practice, there was usually no ambiguity.

To make the system slightly more friendly a facility had been provided to prompt the user if more information was required. For example, if the user types the command *rename* followed by pressing the *return* key the system will prompt for the old situation name and its new name. Some students learned to use this aid but most simply used the system in conjunction with the command summary sheet.

The two other features that were designed to increase the 'friendliness' of the system were the help system and the success/error reporting. Students needed to be encouraged to use the simple help system. In most cases help was confined to syntactic advice. There seemed to be little trouble interpreting either the error or success messages.

In conclusion, the worst features of a command driven interface were mitigated with the help of reference material and a 'prompt the user' facility. These problems can be overcome using a more sophisticated approach which is briefly discussed in chapter 6.

Increasing the Power of DYNLAB

DYNLAB lacks some features which would turn it into a very powerful and expressive medium. These could be added by re-implementing DYNLAB on top of, for example, LOGO and then providing controlled access to the fundamental mechanisms of the base language. The features that are needed include:

- Generalised force functions etc. This would permit, for example, uniformly increasing forces to be applied.

- Measurement primitives. To handle gravitational attraction, for example, the FORCE due to one body attracting another body needs access to the measurement of the distance between them.

- Sensor primitives. It should be possible to sense contact between two bodies —including collisions.

These changes are fundamentally simple but there is one extension which would have a radical effect: the addition of user-extensibility. If the user could create new entities other than MAPs, JOURNEYs and FORCEs and attach new properties to entities then possibilities increase for more complex modelling and for the exploration of a wider range of misconceptions.

Further improvements include the addition of control primitives and a graph interpreter tool which could be used to extract useful information from the graphs constructed by the system.

4.6.3 DYNLAB and Misconceptions

DYNLAB was designed to confront a number of misconceptions —particularly those associated with beliefs about the effect of impulses and forces upon the paths of point masses. At the end of the last chapter it was stated that a system capable of exploring a wider range of misconceptions than ROCKET or TARGET was wanted. This has been achieved even though further extensions to the system would increase the range still further. In particular, DYNLAB can be used to simulate ROCKET. Some further considerations follow.

Limitations

As has already been implied, DYNLAB is limited in terms of the range of misconceptions that can be modelled. For example, DYNLAB cannot be used to handle the set of misconceptions regarding bodies constrained to move along curved paths by, say, moving along the inside of a hollow tube. This would require objects having extension and would introduce the problem of how the student could define the relationship between the hollow tube and the moving body in terms of forces.

The attribution of causality is a problem. At the moment, DYNLAB is designed to require the user to reify forces. That is, a force has to be given an existence which is also separate from the object. This requires a slightly different account of affairs concerning the standard 'story' told about bodies exerting forces.

Possibilities

Some further possible investigations can be undertaken with the current DYNLAB system. As has been already mentioned, investigations based on two interacting bodies might prove very revealing. Likewise, further investigations of speed-velocity and distance-displacement problems are possible.

During the observational period interventions were made very rarely and mostly to explain some feature of the system. The selection of some metaphor(s) was required.

A variety of metaphors can be used to describe any computer-based system. These include metaphors based on objects, databases and actors. The one most frequently used in explaining the system to the students was of the object oriented flavour.

The Object Oriented Programming Metaphor The description of the world in terms of communicating objects is a very attractive one. A message sent by an object needs to clearly specify the object for which the message is intended. In Smalltalk-80, message passing and the various other features have a technical meaning but the imagery is useful for offering some explanation of real world situations and computer systems such as DYNLAB. For example, the command

    + CAR MASS 2KG

can be seen as a message to the object called CAR to add the fact that the mass is 2KG. In Smalltalk-80 the same might be represented as

    car +:mass value:2kg

Thus Smalltalk-80 requires that the selector +:value takes a *keyword message* with two arguments —the first is the property being added and the second is the value. In LOOPS, another system which incorporates object-oriented concepts [Bobrow & Stefic 83], the same might be:

    (SEND ($ car) + mass 2kg)

The syntax of DYNLAB can therefore be made closer to the object oriented approach by such as:

CAR + MASS 2KG

Syntax, however suggestive, is not everything. In practice, the object oriented metaphor was a powerful and useful way of describing the functioning of DYNLAB.

The Database Metaphor An alternative descriptive style requires that DYNLAB be seen as a database consisting of a number of files and records along with a number of actions that can be taken to update the database. A description of:

+ CAR MASS 2KG

is roughly that a file called **CAR** is updated by changing the record labelled **MASS** to contain the entry 2KG. The concepts required for this explanation were judged to be relatively unfamiliar to the computer novices used in the observational period. Therefore, the database metaphor was not exploited.

Concurrent Language Metaphors Consider a message is sent by some object to an object in Smalltalk-80 which in turn sends a message to some third object. Meanwhile, the original message sender has to wait. In other words, Smalltalk-80 is not a language supporting a concurrent view of the world. What is needed for educational usage is a language based on world-like behaviour. For example, Chung has implemented and tested a concurrent version of LOGO for use with control applications [Chung 86]. Various versions of LOGO now include *sprites* which, in principle, offer similar possibilities but not always with the required flexibility. Little, if any, research exists to say how students will handle such a concurrent environment but work is still going on to develop systems that offer some help in managing sprites [diSessa 86].

Chung's results, however, suggest that the students themselves might be aware of the advantages in thinking about things in the real world using some metaphor applicable to a concurrent programming language. For example, the actor metaphor requires a number of independent objects, the actors, to synchronise their behaviour according to some commonly agreed script.

Computational Expressivity

Some languages are more expressive than others. It is just not true that two languages of Turing Power are as good as each other for novices. Some languages permit a description of problems that resembles the 'natural language' description more closely. The search for a language in which to describe dynamics situations suggests that it is not easy to define a single language that is equally expressive for all problems that might be expected. For example, a language which handles the description of objects is not necessarily the right language for talking about continuous phenomena.

4.7 Summary

This chapter started with an analysis of the problems that students have with learning about dynamics and, to a lesser extent, kinematics. A modelling environment, DYNLAB, was described and utilised with ten students to investigate the extent to which they were able to confront their own misconceptions.

The methodology adopted was to provide the students with a misconception test followed by opportunities to model the situations that featured in the test. This was found to be very useful in practice. The modelling of situations was generally successful but the fixed length of time available proved undesirable in that not all the students were able to finish the modelling.

Confrontations occurred and were resolved satisfactorily on a number of occasions. Those who took advantage of these confrontations were often the students who were eventually able to articulate their own beliefs. Encouragement of reflective thinking is one of the proposed advantages associated with the modelling approach.

The results provide further evidence for the widespread nature of a number of misconceptions about dynamics and kinematics. Consider, for example, the occurrence of non-Newtonian ideas discussed in the previous chapter. It was found that the use of DYNLAB had advantages over ROCKET. In achieving a goal such as that posed for students using ROCKET —see figure 4–8— students often appeared to be debugging non-Newtonian beliefs. It proved much easier to discriminate between students with Newtonian beliefs making use of sensible problem solving strategies and students with some misconception.

Some further comments follow on the students' performance:

- Students demonstrated a range of approaches to modelling the geometry of problems. These different approaches illuminate some of the difficulties these students had in modelling the dynamics.

- Some students were unaware of the implications of changing more than one variable at a time. They do not understand that this makes it difficult to infer relationships between variables. Even when only one variable is changed students do not necessarily infer plausible relationships.

- Only one student was able to generate the idea of stopping a ball with a kick and then kicking it towards the target. This student went on to apply the two kicks simultaneously. This is further evidence that students have difficulty in following diSessa's *Learning Path.*

- In some situations, students have difficulty in deciding on the frame of reference.

In addition, other lines of enquiry can be followed. Time did not permit any work on the concept of velocity as outlined in section 4.3.4. Misunderstandings about Newton's third law were also identified as an area for further investigation using DYNLAB —some suggestions were made in section 4.3.4 as to how this might be carried out. Further work is needed on the understanding and use of various graphs.

We now consider how some of the ideas described in this chapter carry over into the electrical domain.

Chapter 5

Modelling in the Electrical Domain

5.1 Why the Electrical Domain is More Difficult

Before discussing the problems of learning the concepts required to understand simple electrical circuit behaviour it is necessary to make out a case as to why this domain is intrinsically more difficult to master than the domain for which DYNLAB was designed. There seem to be three kinds of argument:

- Manipulating the formal system
- Describing causal connections
- Constructing/selecting a model of electricity

These three issues are not entirely separate in that the model selected influences the construction of a causal description.

At the formal level, the problems of manipulating the basic facts and equations related to electrical circuits seem to be a magnitude of difficulty greater than those relating to the dynamics of a single point mass. It is difficult to provide a conclusive argument in favour of such a proposition. It has been pointed out that if handling the formal analysis of circuits is difficult then qualitative reasoning about circuit behaviour is harder. Arons reports that some American university students who can produce reasonable results on a test of their formal analytic ability cannot reason effectively about circuits at an intuitive level

[Arons 82]. Since many British 'O' level students are likely to be required to reason at about the same level as these students we are at liberty to ask whether the problem is mainly caused by the importance placed on such reasoning by the educational system or whether there are developmental factors at work. Arons himself points out that students are not required to take the phenomenology of circuits (inter alia) seriously enough and show reluctance to do so.

The second line of reasoning would contrast the simplicity of the causal account for a point mass moving under the influence of a single force —whether or not this involves action at a distance— with what might be said about even the simplest of electrical circuits.

The third argument is that a large number of analogies can be used —see table 5-1. It would be safe to say that few advocate the use of analogical models for the dynamics of a point mass although Pope has followed up an idea of diSessa's based on the flow of momentum in order to generate an analogy for certain mechanics problems in terms of electrical circuit concepts [Pope 85].

Model	Reference
Mechanical Model (Mass-Capacitance)	see [Macfarlane 70]
Mechanical Model (Mass-Inductance)	see [Macfarlane 70]
Water Flow Model (Incompressible fluid flow)	see [Gilbert & Osborne 80]
Gas Flow Model (Compressible fluid flow)	see [Shire 60]
Heat Flow Model	see [Maxwell 92]
Energy Flow Model	

Maxwell's water flow analogy is quoted by Gilbert and Osborne in [Gilbert & Osborne 80] while Drude's theory of resistance requires the compressible fluid flow model. Early on, Maxwell observed the relation between heat flow and electrical flow.

Table 5-1: Possible Analogical Models

5.2 Difficulties with Electrical Concepts

5.2.1 Problems with Models

A major question is how a computer program can be an advantage in helping the student to formulate a clear model of electrical processes. That there exist some problems for students within this area is not in doubt.

A Ball Bearing Model

A common introductory analogue model for the explanation of the behaviour of electricity in a circuit likens electricity to a large number of ball bearings moving through a tube just wide enough to allow them to pass through unimpeded[1]. There is not much free space between the spheres so, presumably, they move together. As one bearing leaves the wire so a space is created at the other end which can be filled by another bearing.

This model can be used for the pedagogic purpose of discussing the nature of electrical current but there are some problems that must be mentioned. Probably the first thing is that the model is strictly limited in its applicability. This may not be made very clear to the student. The student is likely to have just begun a study of current electricity and should be familiar with a simple atomic theory of matter. Other models of electricity will be used later so, if we heed the warnings of various people (for example, [Holman 75]), then the student should spend a little time exploring this model before moving on to other models.

A further problem is connected with the use to which the model is put. The student is supposed to know something about charge. In particular, that each electron has an identical charge. It is supposed that a steady electrical current through a length of wire can be defined in terms of the number of electrons

[1] See [McCorkindale 80] for an example of the pedagogic use of such a model.

entering the region per second[2]. If we now use our simple ball bearing model to discuss current then there is an immediate difficulty. If we think of increasing the current then we have to increase the number of ball bearings passing through the wire. To do this, their speed is increased. Thus a simple connection is made between speed and current. Unfortunately this is reinforced by the ordinary usage of current which lends itself to the simplified relation that current is proportional to speed. This simple picture of current is incorrect and a more sophisticated model will eventually be needed.

Going back to the primitive model presented to the student, it seems more than likely that the use of this model is expedient but not necessarily advisable. The remedy is to present students with a model which permits a proper exploration of the concept of current. The only difficulty may be the one mentioned previously about the intellectual readiness of the students but, in view of their age[3], there seems to be a good chance that they have attained the level of early formal operations which the problem discussed might be said to demand by theories inspired by Piaget.

Liquids and Electricity

Electrical behaviour in a circuit is commonly modelled using analogies with water flow. One problem associated with learning the concept of current has been described above but there is another.

The usage of the word "current" encourages the usage of "flow" in conjunction with it. This seems natural in the domain of liquids flowing in rivers or pipes but it is less obviously the case with electricity. In historical terms, Maxwell is reported by Shire as explicitly discouraging the connection between the use of the word "flow" and the idea that electricity is a liquid [Shire 60]. Evans

[2]Note that we have introduced a level of indirection here.

[3]Assumed to be at least fifteen.

has also observed the use of this almost unconscious assumption by students [Evans 78]. What is the problem? After all, everyone talks about current flow and terms such as "the rate of flow of charge" abound. The problem is that the use of the word "flow" carries with it the connotations of a liquid model of electricity. Unless this implication is made explicit the student may spend a great deal of time working with the assumption that electricity is effectively a liquid. The danger is that the students will mistake the model for the thing modelled without being aware that they are doing so. This is less likely within the Scottish educational system at present as many teachers use the particulate viewpoint rather than a continuous one —see section 5.6.3 for more details.

In connection with this incompressible liquid model, the standard water pipe model is often presented as a model for an entire electrical circuit. The usual analogy is made between electrical current and water flow, water pressure and electromotive force (EMF), and pump and battery. In addition, there are connections made between flow meters and ammeters and heads of water and voltmeters [Smith & Wilson 74]. We must, however, have strong doubts about the advisability of explanations of electrical behaviour in terms of this model. The essential weakness must be due to the inadequacy of the student's knowledge about both electricity and fluid dynamics. Although they might be expected to possess a richer set of naive beliefs about fluid flow than electrical circuits[4] there is no reason to believe that they are in a position to easily transfer informal notions of fluid flow to formal notions of electrical circuits.

There is also a developmental consideration associated with ideas about current flow. Using the standard water flow model, imagine two pipes with rectangular cross section and steady flows of water through them (viscosity is to be neglected). The first pipe has half the cross section area of the other and the water in the second has half the speed of the water in the first one —assuming, for the moment, that the water in either of the pipes has a well defined speed. Therefore they have the same current. Obviously we would like students to be

[4]This seems to be a common belief but it is not necessarily the case.

able to make the same deduction of equality but it seems very likely that if they were asked which pipe contained water with the greatest current it is believed that a high proportion would reply that it was the pipe with the fastest water. If they are not aware of the definition of current as the volume transported per second then the students have only taken one of the two (quite complex) variables into account and, in Piagetian terms, they have not yet reached the required level of early formal operations. If, on the other hand, they do not understand the definition of current in the case of water what hope have they of learning about electrical current *by analogy*?

Causal Models

Ascribing causal connections to events is a powerful intellectual tool but there are associated difficulties. Illustrative of the consequences of not paying sufficient attention to the causal model presented to the student is the following:

> The electromotive force creates the electrical pressure when charge flows[5]

which can be interpreted as suggesting that the electromotive force creates a pressure which creates a charge flow but only when the charge is already flowing!

The problem of providing a good, usable causal description of the behaviour of electricity in electrical circuits must receive more attention. At the very least, teachers need good stories to tell about sequences of observations of physical phenomena. Just because a perturbation applied to an electrical circuit usually settles down too quickly for the student to follow a chain of significant events in the laboratory does not mean that a good story cannot be taught and learned. Some account is needed as to why temporal sequence of events occur in the order observed —this is close to a description of a chain of causal relationships. The desire for such an analysis may be a 'human weakness' but it would seem very difficult to live without it!

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[5]Found in [McCorkindale 80].

A common approach is to start by telling the first story about electrical circuits in terms of the observation of simple physical events such as the turning on of a switch, the readings on various meters etc. Certain causal associations can be built up but the range of observations normally covered is insufficient to gain the necessary experience to induce a causal account of the effect of perturbing circuits at the required level.

This has the flavour of a 'Baconian' approach to science. It is not the only way but in the absence of more information about the naive hypotheses of the students we are unable to use a more 'Popperian' approach.

Going back to the problems that students have on the phenomenological level, it is believed that students must be helped to build up a causal account of the behaviour of any given circuit. Once upon a time this meant a mechanical model of electricity. Lord Kelvin is quoted as saying that he required such a model (see [Hempel 65]). It would be useful if such an account could be derived from the formal terms of the theory but this is not possible.

We are therefore looking for an analysis of a circuit which 'explains itself' in causal terms. Rieger and Grinberg have attempted to describe systems in causal terms [Rieger & Grinberg 77]. Their development of a list of ten theoretical forms of inter-event causal interaction may prove useful at the circuit analysis level. De Kleer has investigated the possibility of developing a computer system which can, from the circuit topology and the known behaviour of individual elements, deduce the teleology of the circuit [de Kleer & Brown 80]. He criticises the ability of circuit analyses such as those provided by SOPHIE I [Brown et al 75] because they can only generate descriptions of the analysis that do not correspond at all with the way people solve the same problem. Such circuit analyses as provided by SPICE [Nagel & Pederson 73] and used by SOPHIE I are, of course, subject to the same criticism.

He suggests two principles which should form the criteria for deciding that a given device has a robust model. The first he names as the *no function in structure* principle. Roughly, the behaviour of any element such as a resistor must be defined in terms that make no reference to the functional behaviour of any other element. The second principle he names as the *weak causality* principle which states that every event has a direct cause. De Kleer's models for components of electrical circuits incorporate formal quantities such as current, voltage, resistance and time.

Analogue Models

One of the main contenders for an analogue model of electricity is the water flow model which is probably the most widely used one. The limitations are indicated in the SCEEB Physics syllabus in that the analogy is required for the purpose of explaining electrical current but not for potential difference [SEB 82]. The evidence that students do not have too good a grasp of the properties of water circuits[6] does not, of itself, make the analogical comparison of electrical circuits with water circuits invalid. Black has pointed out that if the interaction view of metaphor (and, by extension, analogy) is accepted then comparisons of the two systems may well illuminate each other [Black 62].

There are still, however, a number of advocates who recommend full working water circuits in order to teach electrical concepts. Smith and Wilson describe such a course of instruction [Smith & Wilson 74] —even modelling capacitors!

Gentner and Gentner sought evidence for the generative use of analogy in explaining simple electrical circuits [Gentner & Gentner 83]. They set out to test their predictions:

- That students using the flowing water model would be able to handle parallel and series batteries better than those using the moving crowds model.

- That students using the moving crowds model would be able to handle parallel and series resistors better than those using the flowing water model.

[6]See [Wilkinson 73] for a more detailed account.

They found evidence in support of these hypotheses but there was also evidence of considerable lack of understanding of the way in which water behaves.

Bullock investigated the effectiveness of the water model as a means of learning electrical concepts [Bullock 79]. After a statistical analysis of his results he concluded that the students who had been taught the water model analogy did little better than those who had not been so taught. This was, as one might have guessed, particularly so in terms of their understanding of voltage.

He also incorporated a test of a student's ability to make an analogy between a simple electrical circuit and another, unfamiliar system. He concluded that an electron flow model might prove more successful. There is some support for this as Ormerod discusses the possibility of teaching an electron gas model [Ormerod 78]. Sparkes has implemented a very simple model as a computer simulation [Sparkes 82] but he offers no substantive evidence about its effectiveness for student learning.

It is possible that such a model would prove acceptable as most students will have met a model of the atom which incorporates a simple model of electrons. The SCEEB Physics syllabus for 'O' grade incorporates this requirement in connection with the introduction of electricity. A decision has still to be made about which of several electron models can be used successfully.

It must be said plainly that the preference here is for an underlying electron model of electrical phenomena within circuits. This suggests that we have a multi-layered approach to building a representation of electrical circuit knowledge. Thus, we have at the base level an electron gas model. Above this, we have a lumped model in the standard way together with, perhaps, a qualitative model, which can handle causal explanations of the behaviour of the lumped model. The base level provides possibilities for further analogical explanations.

A Functional Model

A further model is often supplied which indicates the intended function of the various components of a simple DC circuit. The battery is seen as the source of power, the wires as conductors for the power and the resistance as the 'load' or that which uses up the power.

The problem for the computer with such a model is that it would be necessary to deduce the intentions of the user in terms of the circuit's *teleology*. A slightly more complex example than the one above would involve the use of a capacitor in an AC circuit. The program would have to be capable of recognising whether or not the user intended the capacitor to filter out the DC component or smooth out the AC component. At best, the computer program might know about both the essential features of a capacitor and the ways in which it might be used but it would still be extremely difficult to determine the intentions of the user unless the user can specify what is wanted in some meaningful way.

5.2.2 Further Problems: the Concept of Potential

The distinction between electromotive force and potential difference is an obscure one [Warren 65, Page 77]. If we are to expect students to state, for example, that

> The EMF of a cell is the voltage between the terminals of the cell when it is in an open circuit

then we had better clarify what the student must know about electromotive force and potential difference.

As Warren points out, many textbooks pay scant attention to drawing out the distinction between these two conceptually distinct quantities [Warren 65]. Page points out that confusion is found within both technical journals and dictionaries [Page 77]. Further, since potential difference and electromotive force are both measured in volts it is only natural to assume that they are identical but this assumption must be, and is, wrong. The electromotive force of a source is going to be taken to be the energy supplied per coulomb to the circuit. The circuit can, of course, extract energy from the source or return it to the source. Thus this energy supply is reversible. The potential difference between two points inside a circuit is going to be taken to be the work done per coulomb in moving a very small charge from the one point to the other. In the case of the charge's path lying inside a conductor this work will be converted to heat due to the effect of the resistance of the conductor. This is an irreversible usage of energy.

The problem is further compounded in that it is quite common to make up a fiction about resistors in which the resistor is associated with an electromotive force which is always negative. This fiction enables Kirchhoff's Voltage Law to be expressed in a rather neat form but it seems to be 'potentially muddling'[7]. If textbooks for physics undergraduates do not make a clear distinction what hope is there for the pupils of teachers who grew up with these same textbooks?

5.2.3 Further Problems: Resistance

There are problems with the model of resistance presented, the meaning of the term *internal resistance* and the status of Ohm's Law.

Models of Resistance

The way that resistance is pictured must surely depend on the model of electricity to be presented. If we use mechanical descriptions of electrons then we might invoke some equivalent to the macroscopically observed friction force of standard 'O' grade dynamics. If we use a liquid model then we might see resistance as being like viscosity. If we use a gas model then we might interpret resistance via ideas from the kinetic theory of gases and think of energy exchanges between the individual electrons and the nuclei of the conductor. Of course, a modern quantum mechanics model will invoke a different conception entirely. The conclusion from this is that the student's conception of resistance is heavily dependent on the model that s/he has in mind.

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[7]See [Bleaney & Bleaney 57] for details.

It might be thought that a formal definition will suffice. Here is a formal definition of resistance presented by one textbook[8]:

> Resistance is a measure of how much voltage is required to make current flow[9]

There is a serious error in the above statement leading to a very strange notion about electrical behaviour. There is a suggestion that no current will flow at all until the potential difference is great enough! The further problem is that the corrected statement would scarcely be said to be more than an aide-memoire. It does not offer an explanation of the nature of resistance —nor is it a definition of resistance.

The problem of providing an acceptable formal definition is discussed later in section 5.2.3. It is likely that we would need to build in multiple views of resistance into any system capable of offering satisfactory explanations —both formal and analogical.

Internal Resistance

A further problem within the same area is the concept of the internal resistance of a battery or cell. Given that the student can accept that any battery can be thought of as being equivalent to a source of electromotive force together with a resistance in series we then come to the problem associated with the definition of the electromotive force of a cell. It has already been stated to be:

> The electromotive force of a cell is the potential difference between its terminals when the cell is in an open circuit.

This seems acceptable until one looks at the means often suggested as to how this potential difference can be measured. A voltmeter is placed across the terminals

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[8]With the intention, no doubt, that students will learn it for some examination.

[9]Found in [McCorkindale 80].

of the battery! Now that there is not an open circuit what can students do but be confused. Either they are to believe that the voltmeter has not closed a circuit or they are in danger of getting muddled about exactly what is meant by an open circuit.

Within the context of a computer program is it possible to present a clear distinction between electromotive force and potential difference? In a rather trivial way, it is. When a student chooses a battery then it must be one of an appropriate electromotive force —not a particular potential difference. The distinction can also be maintained at the circuit analysis stage. Unfortunately, there is so much conceptual confusion about this point that it will take more than *training* students to use the right term according to context.

Problems with Ohm's Law

Unlike many of the formal relationships in simple electrical circuit theory Ohm's Law is an experimental relationship between the current (I) flowing through and the potential difference (PD) across an object[10] at constant temperature and manufactured out of certain conducting substances:

$$V/I = \text{a constant, known as the resistance } (R)$$

which is rewritten as:

$$V = IR$$

This can be turned into a formal definition of resistance such that every object has a resistance which may not be constant at all.

Now the experimental relationship is very similar to other relationships such as $P = IV$ in that one variable is written as the product of two others but

[10] Although it was not stated in these terms by Ohm who saw the law as applying to complete circuits—see [O'Sullivan 80].

there is no doubt that the logical status of this relationship causes some difficulties. Warren reports that students have considerable problems with Ohm's Law [Warren 65] —partly because of the tendency of teachers and text books to switch between the experimental Ohm's law and the formal definition of resistance.

The problem for text books is that the text may point out the experimental nature of Ohm's Law but graphs of 'experimental' results give little flavour of them being other than graphical representations of a linear law. Indeed, section 5.6.3 suggests that some teachers like the standard Ohm's law experiment because it provides one of the best examples of a straight line graph through the origin that can be obtained through practical work.

DiSessa also makes the point that many students are offered an explanation of Ohm's Law in terms of *p-prims* or phenomenological primitives [diSessa 83]. Thus the potential difference is related to an impetus, the resistance to inertia and the current to the result. The student is asked to see Ohm's Law as a particular case of this general law in which an impetus acts through a resistance to produce a result. The picture is coupled to the idea that the more you try to create an effect the more you will be resisted. DiSessa claims that the causality described by this general 'phenomenological primitive' often provides novices with a way of reasoning successfully about applications involving Ohm's Law but he also maintains that experts are aware that the causality described by saying that the potential difference causes a current is only an aid to visualisation and has no deep meaning (see [diSessa 83]). Therefore, we are offered an explanation as to why students seem to find it much harder to visualise a current causing a potential difference or to describe a situation in terms of conductance.

The deeper problem would seem to be whether naive students always seek some sort of causal explanation of physical phenomena, whether we have educated our students to search for such explanations or whether they have ever been seriously confronted with opportunities which allow a variety of perspectives on the causality of the situation. The last two possibilities seem to have some implications for the construction of physics syllabi. If the first possibility is actually the case then two positions can be adopted: naive students will simply have to accommodate the non-causal descriptions that are offered into their causally oriented frameworks or a serious effort must be made to lead them from their intuitions to the knowledge structures possessed by an expert.

5.2.4 Units and Measurement

Inevitably there are problems with both units and measurement.

Units

Some of the difficulties may be due to the far too early introduction of the new units of the Volt, Ampere, Watt and Ohm. If the students have done some mechanics then it must be a disadvantage not to use the alternative names of Joules/Coulomb, Coulombs/Sec and Joules/Sec although the units of resistance are peculiarly awkward to express being in Joules.sec/coulomb/coulomb. The coulomb can scarcely be evaded as the practical unit of charge. Evans has experimented with unit names which are more suggestive than the usual names. For example, the unit of current is called *glow* while the unit of potential difference is named *shove* [Evans 78]. He adopted the simple but sensible principle recommended by Arons —that the name of a concept should not be introduced before the meaning [Arons 82].

Writing and thinking of voltage as the work done per coulomb can form a useful link with previous concepts in dynamics concerning energy and work. Also, there are useful connections between previous work and watts. Coulombs cannot be linked to previous non-electrical work and the units for resistance are none too friendly.

Measurement

The basic devices available for measurements are the ammeter, the voltmeter and the wattmeter. Since there are a number of different principles —moving coil, moving iron, hot wire, thermocouple and electrostatic— that are exploited by meters it seems sensible to hide the inner workings well away from students. Nevertheless, an understanding of how measurement affects circuits is an essential part of learning about circuits.

5.2.5 Further Problems: Simple Electrical Circuits

The Formal Analysis of Simple DC Circuits

Students in S4 are expected to be able to solve problems associated with currents passing through, voltages across and the resistances of various simple electrical objects provided that these objects form a DC circuit which has attained a steady state. Beeson has produced a learning hierarchy that has been validated with some success which has the objective that students should be able to find potential differences, currents or resistances in circuits with two resistance components in series [Beeson 77].

The number of rules needed to solve such circuits can be listed with apparent ease but there are some difficulties that need to be confronted. Consider a problem taken from the SCEEB Highers Examination in Alternative Physics [SCEEB 81] in figure 5-1.

The correct answer to the question is that the total resistance of the circuit is less than 10 Ohms but that it increases as the resistance, X, of the variable resistor increases. This answer can be obtained by a fairly sophisticated algebraic analysis or by a familiarity with circuits that suggests a more 'intuitive' approach. Note that since the internal resistance of the battery is not mentioned it is intended that the student should discount this as a factor! The formal solution might follow some such path as:

> Let R be the equivalent resistance of two parallel resistors with resistances 10 and 10 + X Ohms respectively
>
> This required some reasoning about series resistors

In the circuit below, X is a variable resistor whose resistance ranges from 0 Ohms to 10 Ohms. The total resistance of the circuit is:

A Greater than 10 Ohms, and increases as X increases

B Greater than 10 Ohms, and decreases as X increases

C Less than 10 Ohms, and increases as X increases

D Less than 10 Ohms, and decreases as X increases

E Always less than 5 Ohms, whatever the setting of X

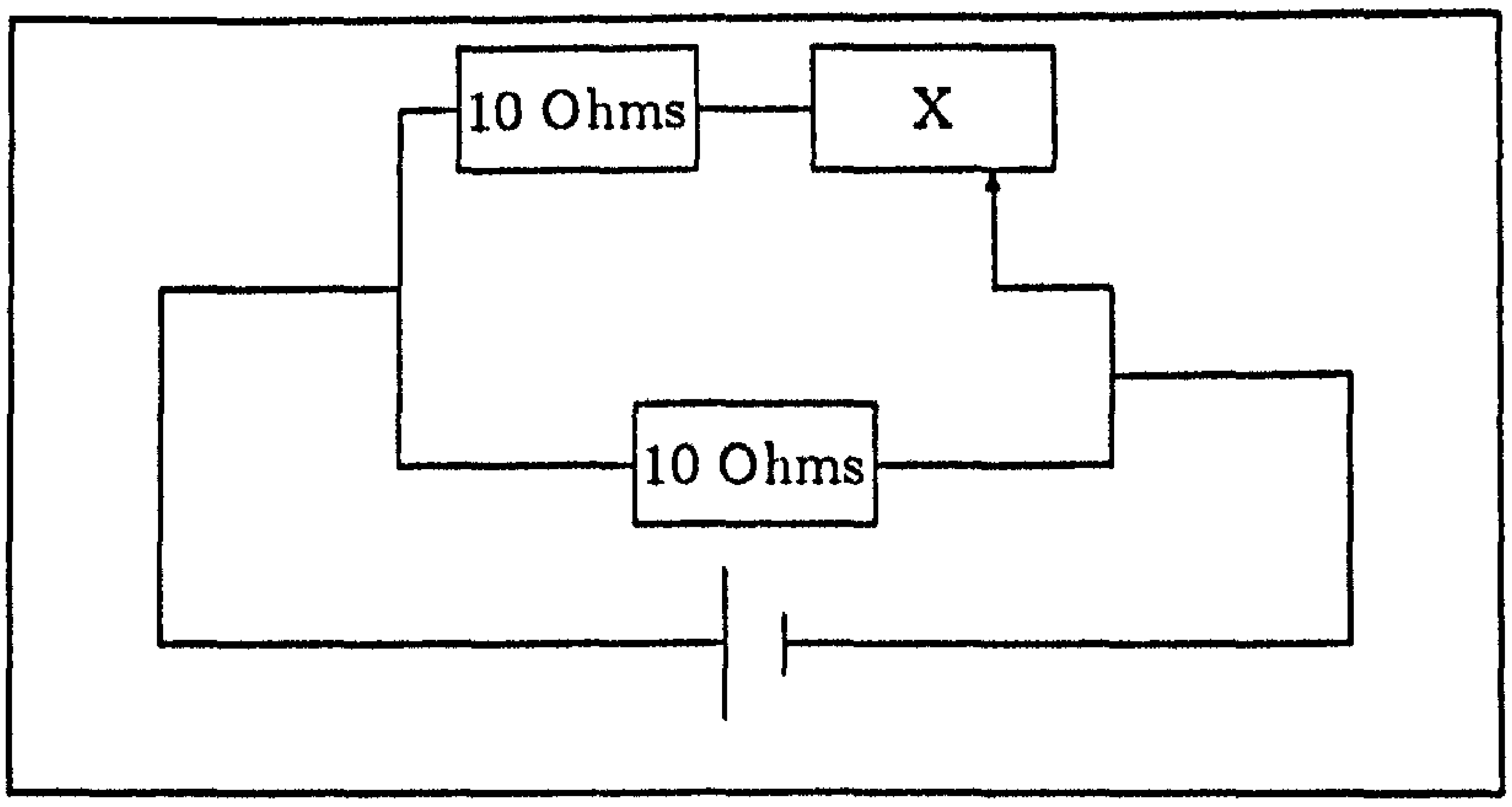


Figure 5–1: A Simple 'O' Grade Circuit

Substituting in:

$$\frac{1}{R} = \frac{1}{R1} + \frac{1}{R2}$$

We get

$$\frac{1}{R} = \frac{1}{10} + \frac{1}{10 + X}$$

We derive

$$\frac{1}{R} > max(\frac{1}{R1}, \frac{1}{R2})$$

$$\Rightarrow R < min(R1, R2)$$

This is often made an explicit rule —that is, the equivalent resistance of a set of resistors in parallel is less than the smallest resistance

Substituting, we get

$$\frac{1}{R} > max(\frac{1}{10}, \frac{1}{10+X})$$

$$\Rightarrow R < min(10, 10+X)$$

So the equivalent resistance is always less than 10 Ohms

Also

$$as\ R2 \rightarrow \infty,\ \frac{1}{R} \rightarrow \frac{1}{R1}$$

This rule is rarely mentioned in any school textbook

$$\Rightarrow as\ 10+X \rightarrow \infty,\ \frac{1}{R} \rightarrow \frac{1}{10}$$

$$\Rightarrow as\ X \rightarrow \infty,\ \frac{1}{R} \rightarrow \frac{1}{10}$$

$$\Rightarrow as\ X \rightarrow \infty,\ R \rightarrow 10$$

which, together, implies

As X increases so does the equivalent resistance R

The burden of the algebraic solution can be reduced by rôte learning of certain principles but while this strategy may work for some questions in an examination it can only be maintained with some difficulty that it has enabled students to improve their understanding of electricity. A system which allows the user to build the above circuit, adjust the variable resistor and observe the value of the equivalent resistance might well prove to be a valuable means of building up a background of experience with electrical circuits.

Taking another (slightly modified) example Highers question from the 1978 Higher Physics Paper 1 [SCEEB 81], we have a different kind of problem[11] —see figure 5–2. The correct answer to obtain a null deflection on the galvanometer is

In the Wheatstone Bridge shown below, a small current is flowing through the galvanometer G. What would you do to balance the current?

A Increase the value of P by 6 Ohms

B Increase the value of Q by 6 Ohms

C Increase the value of R by 6 Ohms

D Increase the value of S by 6 Ohms

E Insert a 6 Ohm resistor in series with G

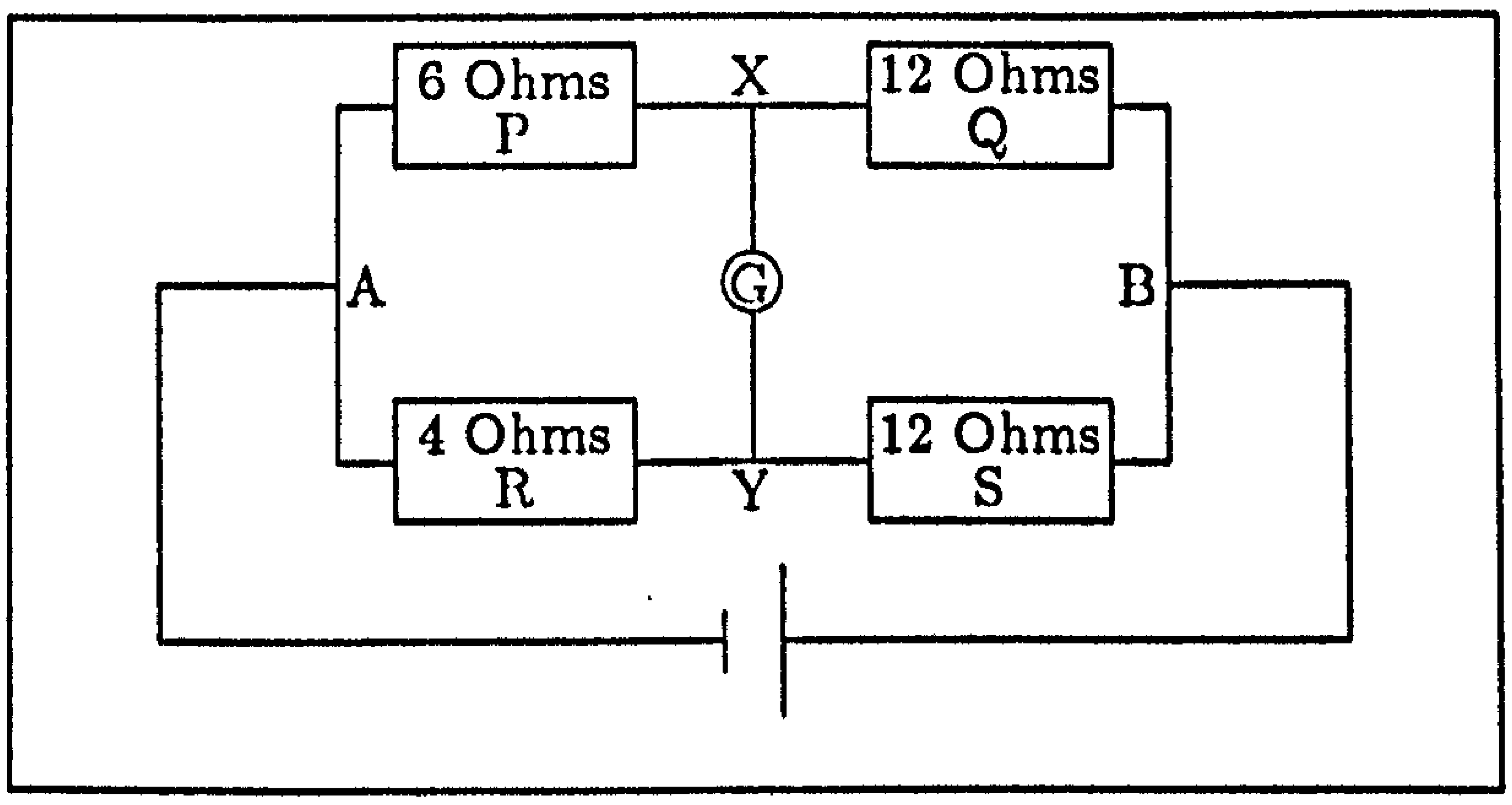


Figure 5–2: A Wheatstone Bridge Problem

to increase resistance between X and B by 6 Ohms. One solution requires some impressive formal reasoning:

$$I_{XY} = 0 \Rightarrow PD_{XY} = 0$$

No current for null deflection —application of Ohms Law

$$PD_{AXB} = PD_{AYB}$$

[11]Note that the labels A, B, X and Y have been added to the diagram.

PD between two points is independent of the path taken between the two points

$$PD_{AXY} = PD_{AY}$$

As above

$$PD_{AXY} = PD_{AX} + PD_{XY}$$

Additive law for a series circuit

$$PD_{XY} = 0 \Rightarrow PD_{AXY} = PD_{AX}$$

$$PD_{AX} = PD_{AY}$$

similarly

$$PD_{XB} = PD_{YB}$$

together, these produce

$$\frac{PD_{AX}}{PD_{XB}} = \frac{PD_{AY}}{PD_{YB}}$$

By no means is the student likely to find this step an easy one. From this point, some relief can be given by the principle that, for two resistors in series, the PD's are divided in the ratio of the resistances. This depends on the observation that, since $I_{XY} = 0$, P and Q are effectively in series. The same with R and S. Hence:

$$\frac{R_{AX}}{R_{XY}} = \frac{R_{AY}}{R_{YB}}$$

If we increase R_{BX} to 18 Ohms, we have

$$\frac{6}{18} = \frac{4}{12}$$

The issue can be avoided by teaching students the above, final result as an extra formula to be learned but this strategy simply evades the difficulties involved in understanding the Wheatstone bridge. No doubt the most able students can handle this problem but it requires a level of formal reasoning that many would say is absent from a large percentage of seventeen year old students.

The question is how to build up some understanding of the behaviour of such circuits without requiring too high a level of mathematical performance. This problem has been recognised, inter alia, by Champagne in the domain of mechanics who believes that the student is often required to spend far too much time struggling with the mathematics rather than with the physics contained within the relevant situation [Champagne et al 80].

5.3 Misconceptions about Electrical Concepts

In section 1.4.4, misconceptions were discussed in terms of being partly due to the *alternative frameworks* that the students themselves hold about the real world [Driver 81]. Here, examples of misconceptions relevant to the context of simple electrical circuits are introduced.

Misconceptions about Current

An early piece of research which illustrates something of the alternative frameworks that students can hold concerning the nature of electricity was performed by Tiberghien and Delacote [Tiberghien & Delacote 76]. They asked ten French children to light a bulb given a battery, a bulb and a length of wire. These children varied in age from seven to thirteen and many of them had some difficulty in lighting the bulb. They produced a number of interesting arrangements which are associated with the 'unipolar' model of current electricity. Essentially, many of them tried to exploit the wire as a means of joining only one of the two battery terminals to the base of the bulb. Even when the student can see an arrangement which functions correctly they were still likely to describe the 'flow' of electricity as going from the battery and into the bulb and, by implication, not coming out again.

A more sophisticated 'bipolar' model involves the use of both terminals of the battery but only the base of the bulb —perhaps because the terminals used are the only obvious ones. Here, it would seem that the student possesses a model of electricity which can be associated with a two fluid theory which appeared in the history of electrical theory. The student still sees the electricity as leaving each of the battery's terminals and entering the bulb without going any further.

Fredette and Lockhead performed a similar set of experiments and obtained similar results with a sample taken from amongst university students [Fredette & Lockhead 80]. They would seem, however, to see the error of the students as caused in part by an incorrect application of the concept pair of source-sink. This pair of concepts occurs quite frequently[12]. The application of such a general principle is suggestive of a particular natural framework from which the student may view electrical phenomena.

It is important to note that some students sounded as if they were familiar with electrical concepts and some had even taken relevant courses and yet they still had deep seated problems.

Osborne has outlined a number of problems with electric current using the "Interview about Instances" method [Osborne & Gilbert 80a]. Students between seven and eighteen were interviewed with the finding that some older students provided responses that varied only a little from the younger pupils.

One situation required students to answer the question

Is there an electric current in the battery?

about an unconnected battery. The responses quoted are stated to illustrate a 'container' theory but it is possible that batteries might be seen as containing a flow of electricity which is then diverted through the terminals when a load is placed across them. Osborne further developed his ideas by describing three possible incorrect models of electrical current [Osborne 81]. These include a

[12]Significantly, in fluid flow theory.

model in which no current returns to the battery, one in which there are two currents —a positive and a negative one– which he names the *Clashing Currents* model.

Shipstone has expanded on this work by establishing four models for electrical current which include the clashing currents model [Shipstone 84]. The evidence is that the use of this model diminishes as the students get older. Osborne quotes a figure of less than 5% for students in the equivalent of Scottish secondary schools.

There are two other 'buggy' models described. One requires that the current flows in one direction but gets weaker. The other requires the current to be shared out equally —but the current is not conserved. This latter model increases in usage to peak at the equivalent of Scottish S3. Shipstone attributes this to confusions between current and power-based concepts. In discussing the failure of students to use water analogies effectively, Gentner and Gentner suggest a generalised strength attribute which bundles together velocity, pressure, force of water and rate of flow [Gentner & Gentner 83]. Something like this seems to be part of student's understanding of electrical circuit behaviour.

A most interesting result that Shipstone found was clear evidence of a *Sequence Model*. That is, if a circuit is altered, the effect propagates forward with the current but not against the 'flow'. This belief may be very widespread amongst teachers as 39% of physics graduates training to be teachers used the sequence model.

Misconceptions about Resistance

Johnstone and Mughol investigated the understanding of the concept of resistance in a study based on both interviews and the performance of a diagnostic test by a large number of students in years S2 to S5 [Johnstone & Mughol 78]. In particular, they focussed on the relationship of resistance to the length and the thickness of a conductor of uniform cross section.

Their conclusions included the belief that all the students were aware of the need for a closed circuit if current is to flow. This conclusion is at odds with the work of Fredette and Lockhead [Fredette & Lockhead 80] which can be explained by looking at their procedure for determining whether someone actually had such a belief. Johnstone and Mughol's evidence appears to be based on the ability of students, when prompted by a circuit diagram, to answer correctly as to whether current flows in a circuit.

Their results indicate, for example, that students in S2 to S4 seem to believe that resistance is proportional to the 'amount of material'. Students in S5, however, appear to know that resistance is inversely proportional to the cross sectional area of a piece of wire. Their main recommendation is to that the concept of *conductance* might well be easier to teach than that of resistance.

Misconceptions about Potential

Archenhold discovered a number of misconceptions about potential which included:

- The charge is less once it has been through a resistor ...so there is a potential difference

- The potential across a resistor is the difference in the number of electrons at either end

- A potential is a store of electrons

He concluded that students confuse concepts of work, field, force, energy and potential [Archenhold 75]. Johnstone and Mughol also reported widespread confusion about the difference between the concepts of potential difference and electromotive force and between the concepts of voltage and power [Johnstone & Mughol 78].

Beeson and others have reported that students have problems identifying circuits that are topologically equivalent [Beeson 77]. Caillot believes that students have some form of prototypical view of what constitutes two resistors in series or parallel in a geometrical rather than topological sense [Caillot 84].

Cohen, Eylon and Ganiel devised a 'questionnaire' to investigate a number of misconceptions about electrical behaviour in simple circuits. This was applied to both students in grades eleven and twelve (equivalent to Scottish S4 and S5) and to some teachers. Most questions involved making qualitative decisions —usually about the consequences of modifying some circuit [Cohen et al 83].

One of their main hypotheses is that students see current as the prime concept rather than potential difference. As an illustration, they point out that students often regard a battery as supplying a constant current rather than a constant potential difference. Their other main hypothesis is that students explain changes in a circuit using a 'local' analysis.

The idea here is that any change made to the circuit will propagate changes throughout the circuit. Thus there is a local change and a global one. The implication seems to be that if object X is modified then some property values of X are changed and these changes are the local effects. On the other hand, this distinction may not be general enough to handle the situations they describe involving the addition of elements to a circuit.

Suppose that the term *primary focus* is defined so as to stand for an abstract object to which students have their attention drawn. It seems that Cohen, Eylon and Ganiel regard the primary focus as some specific, single object such as a resistor. This means that the distinction local/global is all that can be captured. Finer distinctions need to be made. For example, if a resistor is added in parallel to another resistor it may be more fruitful to see a fragment of the circuit associated in some way with the initial resistor and the final, parallel combination. Thus the idea of *slices* introduced by Stallman and Sussman may have some utility here [Sussman & Steele 80]. Hence the idea of *primary focus* being associated with an *abstract* object.

Cohen, Eylon and Ganiel's questionnaire was adopted as the basis from which the misconception test was constructed —although with some non-trivial modifications.

This test was used extensively throughout the observation period.

5.4 Previous Work

5.4.1 A Game Approach

Megarry produced the board game CIRCUITRON which was designed to reinforce the basic facts and principles about circuits that had already been encountered and to develop laboratory skills (see [Ellington et al 81, Megarry 77]). The game consists of two teams competing against each other in trying to build complete electrical circuits of as large a 'value' as possible. It would seem that there is a rough correlation between value and complexity since wires have the least value and ammeters have the most. There are five levels of play which correspond to the progress that the student makes through a sequence of teaching points. Thus the game is designed around a small number of explicit objectives. The game has been the subject of evaluation with favourable results although it was found that improvements in performance were more likely to occur in the case of simpler teaching points. One conclusion was that one needed reliable feedback in order to play the game with greater educational success. An experimental system was built at IBM into an interactive computer system called TRICIT [Bloomer 76].

Thus there is some indication that building a simulation which can then be checked for correctness is likely to have some educational value along the lines suggested by Megarry. A possible improvement is for a system to demonstrate the correct functioning of the circuit rather than simply giving a yes/no answer.

5.4.2 Using Batteries and Bulbs

Evans has devised a course which introduces electrical concepts in a more informal and more qualitative manner [Evans 78]. He also uses, among other apparatus, batteries, bulbs and wire. Initially, the bulb is used as a current indicator. Figure 5-3 is a typical circuit. Arons has also advocated the use of

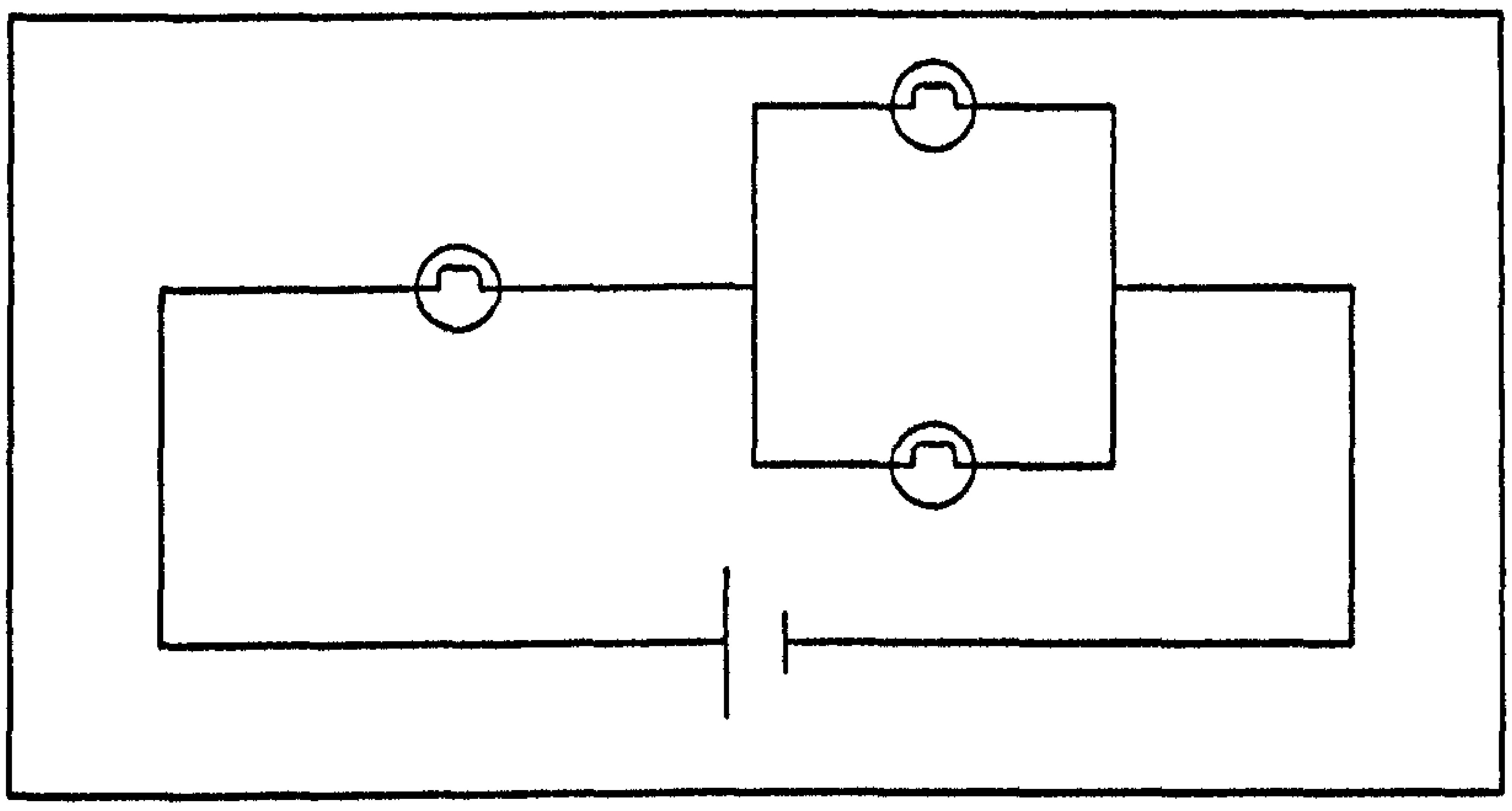


Figure 5-3: A Circuit Using Bulbs and Batteries

such circuits to teach simple electrical concepts [Arons 77]. The SCEEB Physics syllabus also suggests the use of bulbs as primitive current meters to establish such facts as the current is constant at every point of a simple series circuit [SCEEB 76, SEB 82]. Bork has also produced a CAI program based on similar ideas [Arons et al 81].

The course that Evans has produced, however, is more rigorous than the approach hinted at by the SCEEB syllabi. He avoids the introduction of units such as voltage, amp and ohm for a long time while the students familiarise themselves with the qualitative phenomena themselves. The water analogy is used to introduce the idea of current, and voltage is introduced in terms of resistance and current as he holds that voltage is the most abstract idea of the three. Thus Ohm's law is used to define voltage! This must be seen as a weakness on the theoretical level as Warren has pointed out the confusions that arise from not clarifying the logical status of Ohm's law as an experimental law [Warren 65]. Cohen, Eylon and Ganiel also believe that leaving the introduction of voltage so late will reinforce the belief that current is the primary factor [Cohen et al 83]. Meters are left alone on the assumption that they require a deeper analysis than is necessary for an introductory course.

5.5 The Design of ELAB

ELAB is an *Electrical Circuit Laboratory.* It was initially written in Berkeley Pascal and debugged on a Vax 11/750. It was then rewritten in APPLE PASCAL, a variant of version 2.1 of UCSD PASCAL. ELAB runs on a 48K APPLE II computer with a language board and two disk drives. It was designed in the summer of 1983, coded during the winter and tested with students during the spring term of 1984.

5.5.1 An Overview

Briefly, the "Electricity Laboratory" is an environment within which the student can set up a number of simple electrical circuits, observe the results of a steady state analysis and then modify the original design in order to obtain the circuit or output required.

Figure 5–4 provides a schematic overview of the computer system ELAB. By

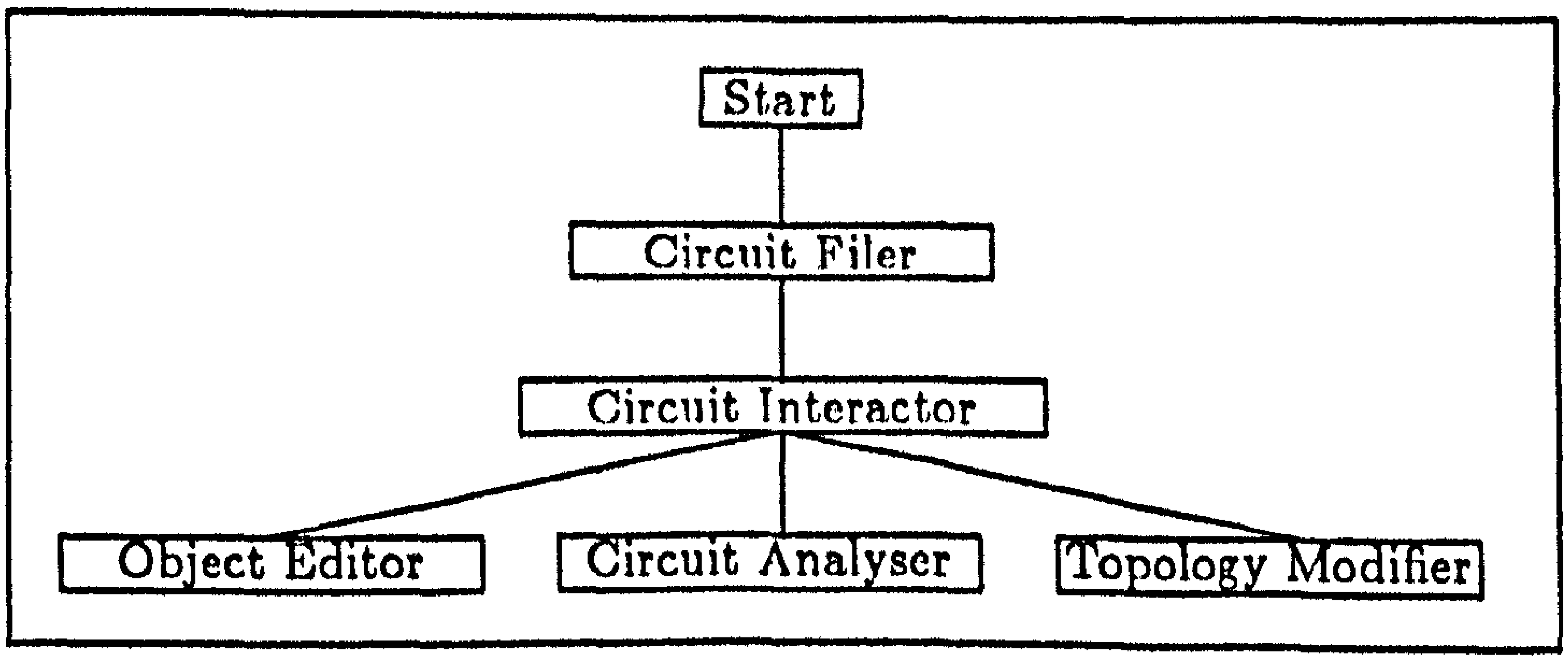


Figure 5–4: An Overview of ELAB

comparing this with figure 4–4, it can be seen that, at this level of detail, the system is simpler than DYNLAB. As many features were based on the design for DYNLAB, attention will be drawn, for the most part, to significant differences between ELAB and DYNLAB.

In the first version of ELAB, the *circuit* is the primary element of description of some situation.

The *Circuit Filer* provides the means for choosing a specific circuit, building or destroying a named circuit and so on.

The *Circuit Interactor* manages the student's interactions with the rest of the system. This enables the student to run the *Circuit Analyser*, change the topology of the circuit through the *Topology Modifier* or alter some Object using the *Object Editor* and tailor the output in a simple way.

As with DYNLAB, the object oriented metaphor is exploited.

5.5.2 The Domain

The basic electrical concepts incorporated are those associated with the steady state analysis —either AC or DC— of simple electrical circuits. This includes:

Current	Potential Difference
Resistance	Electromotive Force
Capacitance	Inductance
Power	

No explicit references were made to the concepts of:

Charge	Resistivity	Time

Unlike DYNLAB, the current version of ELAB does not require the user to 'get the units right' when entering the value of some quantity. It was decided that the units issue would not be addressed by the first version of ELAB.

5.5.3 How to Use ELAB

The parallels with DYNLAB are continued.

Simple Usage

The student is first offered a set of 'situations', or circuits, which have previously been prepared by the teacher (or, possibly, a student). Accompanying the situation chosen is a worksheet which sets the student a goal to be achieved.

Once the student has chosen some circuit to explore and selected the command to RUN, the system makes an analysis and prints out, as a default, the currents associated with each element of the circuit.

When the analysis is terminated the student is free to interact with the system to change the circuit. At first, this need not involve any topological changes but the more able student will want to create circuits, analyse and save them for another occasion.

The student will, however, want to replace objects in the circuit. That is, the student may well wish to use different batteries, resistors etc.

Advanced Usage

This involves the student constructing circuits. There are worksheets designed to guide the student —but students might be given the freedom to design their own circuits according to their own interests.

The student now has to master the tools provided for creating instances of objects and manipulating the circuit topology.

The Circuit Filer

New circuits can be built and old circuits renamed or destroyed.

The Circuit Interactor

The circuit interactor provides the interface with the heart of the system. In particular, it provides for displaying different kinds of information obtained from the analyser:

Current	Potential Difference
Power	V/I

For a DC circuit, the current and the potential difference are always given a direction. The convention for potential difference is that the value given is the drop in the direction indicated on the screen. With regard to power, a positive number indicates a loss of electrical energy into some other form. A negative value will indicate that energy has been converted back into electrical form.

For an AC circuit, the result will be the corresponding RMS value but this may change with a later version which will offer graphical output as an option. Of course, no sign is given to these RMS values and the power output by the AC source is not shown.

The 'V/I' option prints out the 'experimental' value of the potential difference divided by the current —where it is possible to do so. The utility of this feature is that it permits an exploration of the constancy of V/I for objects such as capacitors and bulbs. Since, in real life, bulbs are not ohmic and since, in this program, bulbs are ohmic there is room for discussion with the student about the relation between reality and the idealised world of the program.

The Object Editor

The basic types of electrical object together with their attributes are shown in table 5-2. The bulb's attributes refer to the wattage delivered for the designed voltage. Also note that resistance wire was referred to as 'thin wire' throughout ELAB although the thickness could be considerable. This was prompted by the need for brevity.

Object	Properties	
Battery	emf	resistance
ACsource	emf	frequency
Resistor	resistance	
Resistance Wire	length	thickness
Capacitor	capacitance	
Inductor	inductance	
Bulb	wattage	voltage

Table 5–2: Electrical Object Classes and their Attributes

All these classes of object have two terminals —on opposite sides. Instances of these classes are represented in the Circuit Window as the symbol for the object class together with the name given the instance by the system.

On selecting an object class, an instance is created in a set location along with the default values for the class. The Topology Modifier is now invoked to position the object.

The Circuit Analyser

Basically, the analyser is run and the currently requested information is printed out on the screen for each component of the circuit. This information will stay there until the user chooses some other system action.

Note that, in order to fit the textual information on the circuit diagram, the entire circuit is redrawn to make the maximum use of the screen.

If the analyser encounters a badly constructed circuit, it reports the problem. For example, it cannot analyse two distinct circuits —or a circuit that is not completely connected. On the other hand, it can handle short circuits.

The Topology Modifier

On the creation of an object, an instance of the object is placed in a standard location, the top left hand side of the screen, awaiting the student's commands to position it. ELAB sends a help message to the Message Window.

The current method was chosen to use the same keys and key functions as used for screen editing in APPLE BASIC on the grounds that some students might find the transition easier.

Inevitably, there are constraints on where objects can be placed. The student, on attempting to put an object in an illegal location, is given a simple error message to indicate that the object must be repositioned.

Conversely, destroying objects is currently more difficult than it should be as an attempt to destroy a partially (or completely) wired object will fail. The student must 'unwire' the object completely before destroying it. This indicates a close connection with real life in that, in the laboratory, it is not possible to rip items from a circuit and still leave the circuit complete. The object must be disconnected.

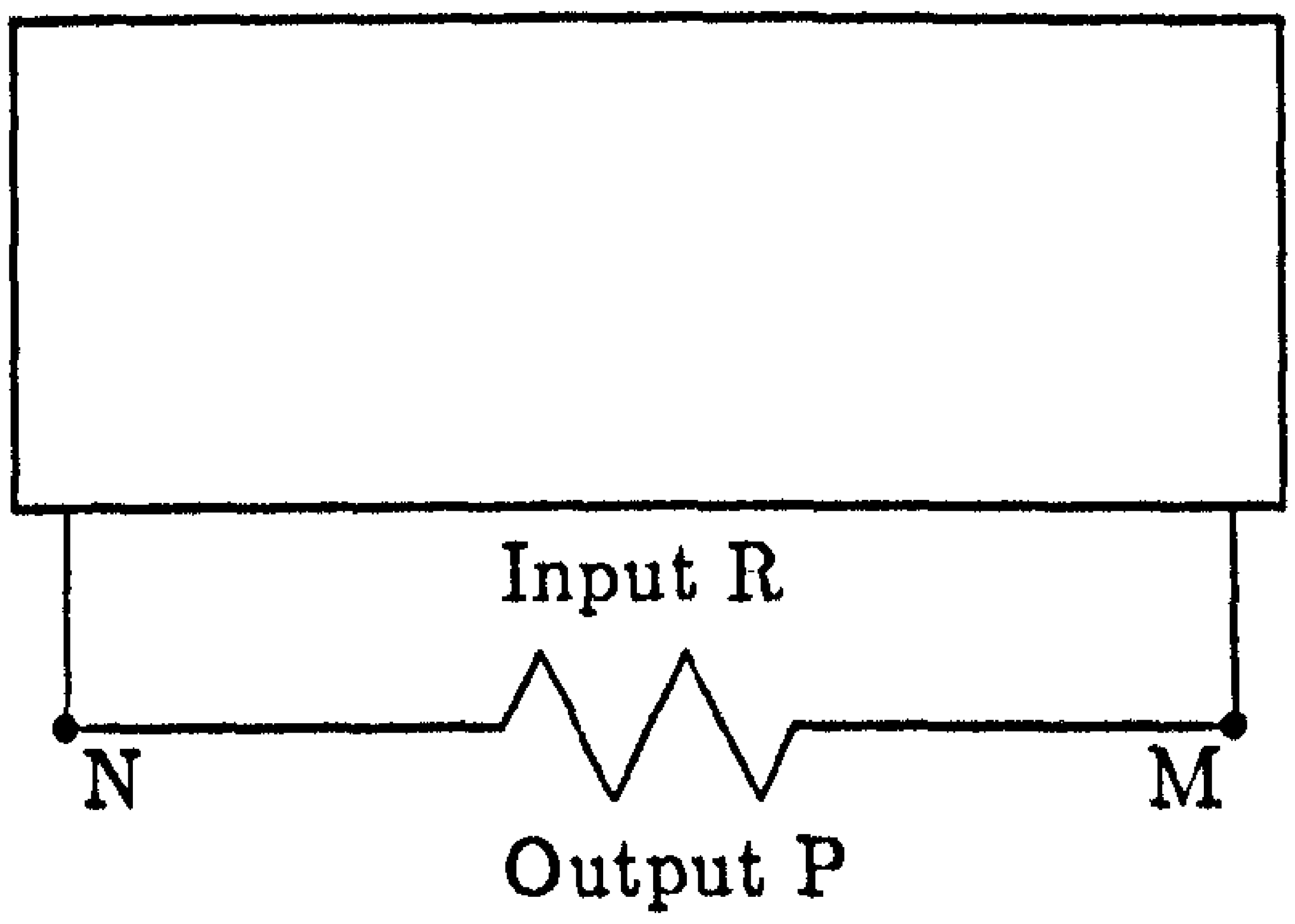
If an attempt is made to move an object already connected then the current version requires that the object is disconnected first. Two operations that, to be consistent, should also require disconnection are those of rotating a connected object and swapping two objects around.

Wiring and unwiring both use the same basic cursor commands as used in positioning an object. Again, attempts to wire or unwire objects in an illegal way are accompanied by simple messages to indicate failure.

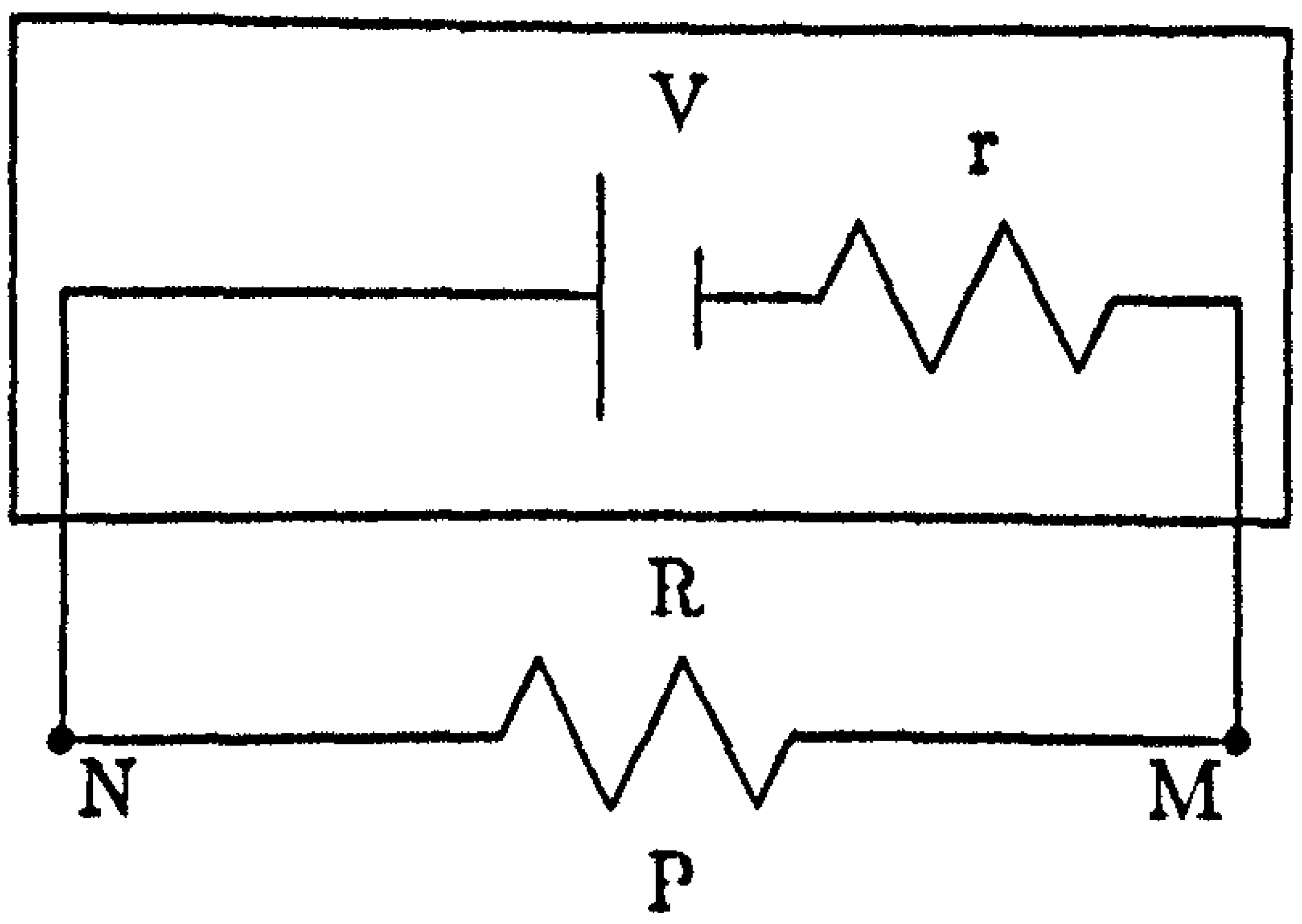
Wiring may start from a position on a link and end on a link. To prevent links crossing over the wiring process is automatically terminated when the link arrives at a legitimate object or another link. An object is legitimate if there is at least one free terminal.

5.5.4 Designing a Circuit

A completed circuit can be seen as a program required to produce certain fixed outputs. If the circuit is open with, say, two free terminals then it is possible to see the circuit as a function with N arguments where N is the number of parameters that can be varied. It would, however, be more accurate to say that this defines an N+1 argument relation. The diagram below illustrates a black box view of an open circuit with terminals M and N. In one mode of use, the required input is a load placed across the terminals and the output is the electrical power converted to heat. The open circuit acts as a function mapping the input resistance to the output power.



If we look inside the box:



It can be seen that there are two constants used to define the function and that there are a number of local variables that might be required to generate the output: in particular, the current through the battery and the potential drop across the internal resistance. Nowhere however is there any mention of how the analysis is to be generated.

This suggests an important distinction between designing a circuit and writing a program for DYNLAB. This distinction is basically the same distinction between procedural and declarative programming languages. Examples of the former require the specification of how certain states of affairs are to be brought about —LOGO is a good example of such a programming language. On the declarative side there is Prolog which is an example of a logic programming language [Kowalski 79, Hogger 84]. Here, the aim is to declare relationships between quantities without specifying how these relationships are to be achieved. Borning believes that Thinglab can provide a limited example of declarative programming [Borning 85a].

Taking the analogy of a circuit as a function then the task of designing a circuit is like writing a declarative program. A well formed circuit is one that conforms to the circuit syntax and the circuit analyser runs the 'program' and reports run-time errors.

Using a graphic interface to define a circuit means that the system has to interpret the user's diagrams into a suitable data structure that can be manipulated by ELAB. The general problem of defining functions and relations graphically requires a much more sophisticated mechanism as illustrated by recent work by Borning in developing Thinglab [Borning 85b].

5.5.5 System Messages

The system messages were designed to report on electrical problems with the circuit and mistakes in assembling the circuit. A small number of help messages were also provided.

The principle that actions resulting in consequences not visible to the user should entail a success message was adhered to.

5.5.6 Support Materials

As with DYNLAB, a number of different sorts of support material were provided. A manual explaining the system, a set of six introductory worksheets, a set of ten worksheets based on the misconception test, a set of six worksheets for more open ended work on DC circuits, a set of four worksheets for similar open ended work on AC circuits and some other material to help students with the system.

The four worksheets on AC circuits were not used extensively. Only one student in S5 who finished very quickly did any work with AC circuits. Basically, however, the students selected had not covered enough AC theory to make use of the project sheets as designed.

5.5.7 The User Interface

Essentially, the screen is divided into five windows which always appear in the same places. These windows represent:

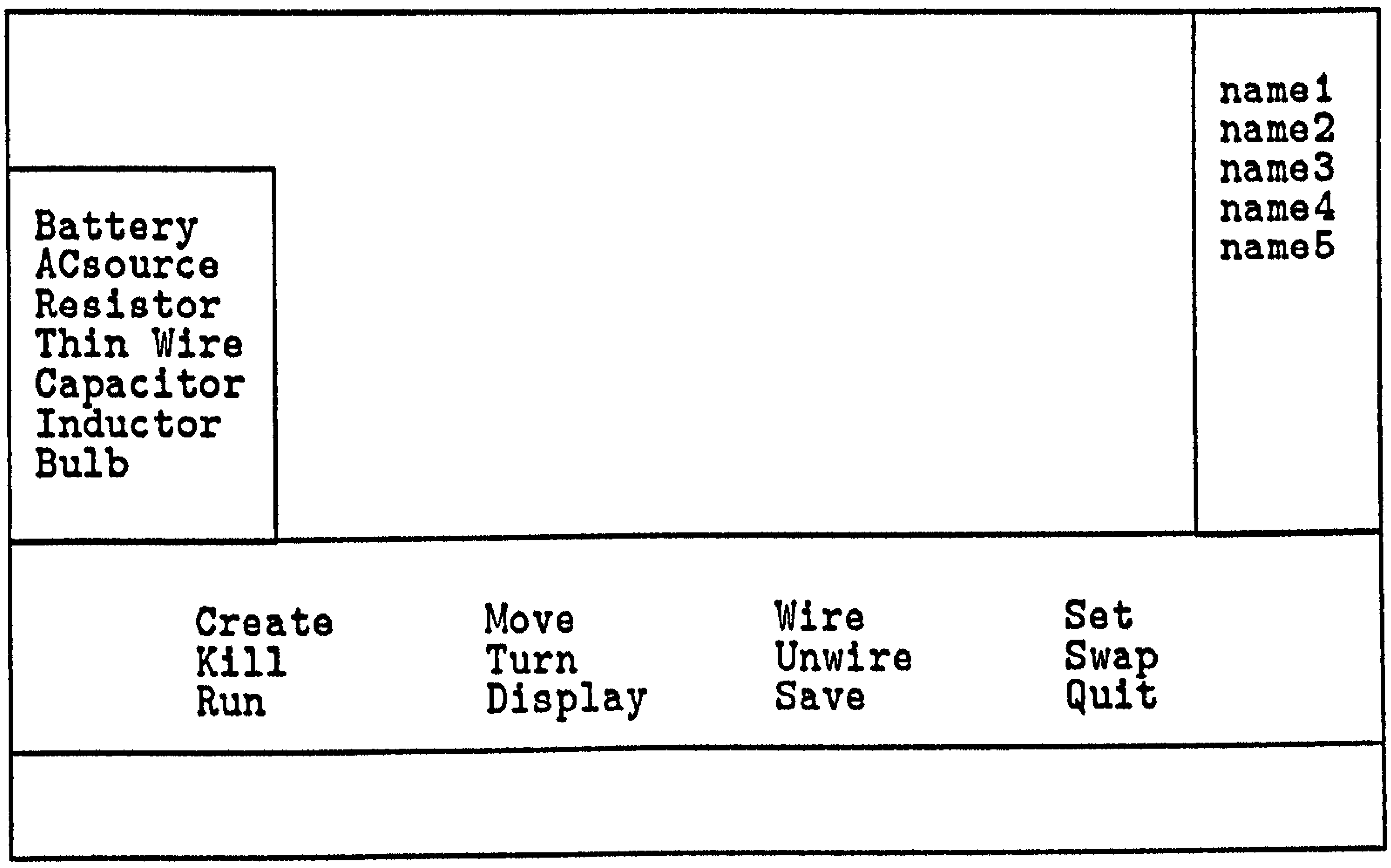
Command Window the set of top level commands that can be issued found towards the bottom of the screen

Class Window the set of object classes, each class represented as an icon, found on the left hand side of the screen

Instance Window the set of names for the instances of the main object classes

Circuit Window the view onto the circuit being constructed

Here is a representation of the screen layout:



The selection of a command from the bottom menu, an object type from the left or an object name from the right involves moving cursors with the space bar until the cursor sits over the required item. Selection is made by pressing the RETURN key.

When issuing commands from the Command Window, depending on the option, the user may need to make further selections from the Class Window or the Instance Window.

Most of the student's use of the keyboard, however, involves moving a cursor around the Circuit Window. There are two kinds of cursor activity in this window: those which affect the instances of the main classes of electrical objects and those that affect the links between these elements.

There is a further window, the Message Window, which is used for written communications between the student and ELAB. Besides giving error, success and help messages, it is also used when the student needs to examine or set the value of an attribute for an instance of some class.

Throughout, highlighting is used to draw the attention of the student to active areas other than the one in which the circuit is being constructed. That is, an active area is one in which a communication of some sort is supposed to take place. This applies to the Message Window as well.

5.5.8 The Set of Commands

The range of commands available are now briefly described.

create: Create an instance of a particular object class

move: Move an unconnected object

wire: Indicate that a circuit connection is to be made

set: Set the value of the property of a particular object

kill: Remove an unconnected object from the circuit

turn: Turn an unconnected object through 180 degrees —or a connected object through 90 degrees

unwire: Indicate that a wire is to be deleted

swap: Swap two objects over

run: Run the circuit analyser

display: Choose which of {Current, PD, Power, V/I} to display

save: Save the current circuit

quit: Leave the circuit interactor

The selection of any of these commands is may require further selections. The *only* command that necessitates use of the keyboard[13] is the *set* command.

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[13]Although the keyboard is used for all the commands, all the other commands could be used with alternative devices such as a puck, mouse, etc.

5.5.9 Discussion of the Design

ELAB was designed to help students learn electrical concepts while experimenting with circuits, batteries and so on.

If the student is asked to attain some goal such as the design of a circuit to fulfill some explicit function then ELAB becomes a useful tool. For example, ELAB can be used to rapidly assemble both the components and the circuit itself. It can also be used to measure the (simulated) voltages across objects. It was hoped that the student might be freed from a number of laborious tasks enabling greater concentration on the more abstract properties of circuits.

Some of the design issues need further comment. These will be divided into several sections:

- The User Interface
- Objects
- The Circuit Analyser
- Topological Issues

The User Interface

DYNLAB suffered in part from the *mode* problem. That is, certain commands could only be given in certain contexts. It was decided to *flatten* the interaction space so that (almost) all the commands could be given from anywhere in the system.

Further, because of the amount of typing in the DYNLAB interface, it was decided that ELAB should use an interface which required as few keystrokes as sensible. Therefore a cursor driven menu system was selected.

Objects

We discuss the properties that objects may take, property values that are associated with the properties and how to create new objects.

Object Properties The attributes assigned to some of the objects are gross simplifications of reality. For example, the resistance of a metal is roughly proportional to its absolute temperature at room temperatures and higher [Meaden 66].

The assumption is that resistors behave in an ohmic way. That is to say, the resistance remains constant for different currents given that the temperature of the resistor is constant.

An EMF supply is most likely to be associated with a battery of some kind which, as a result of Thevenin's Theorem, can be regarded as a pure EMF in series with a resistor (see [Shire 60]). The class of Batteries therefore has both electromotive force and resistance. An easy extension would have been to include the storage capacity of the battery. This would enable a further distinction between *primary* and *secondary* cells. The distinction between these two cell types is that primary cells cannot be recharged by reversing the normal direction of the current while secondary cells can be recharged. Therefore, if we wished to capture the behaviour of cells by maintaining a record of how much charge the battery can deliver then we must know whether we are dealing with a primary or secondary cell. It would be easy enough for the program to maintain this information but students might not initially be aware of the distinction.

To summarise, the general approach used in the first version of ELAB attaches the minimum number of object properties to each object class. Any future version of ELAB would provide for users to create arbitrary property classes in addition to the ones currently built into the system. To do this it will be necessary to extend the system in a radical way.

Object Property Values For the moment, consider the student who wants to select an instance of the class of batteries. ELAB chooses a unique identifier for the battery —suppose that the name "bat1" is chosen. The EMF of the battery is to be specified —but what about the internal resistance? Should ELAB prompt the student? The decision taken was to let the student work with batteries with zero internal resistance as their default value. Later, the student can change the internal resistance when the concept is introduced in the physics curriculum.

Generally speaking, if the student fails to 'fill a slot' in the description of an instance of some object then there will be default values which refer to an appropriate 'standard' object. This is very close in spirit to the idea of Bork's controllable worlds [Bork 78]. As he points out, such an approach allows the student to start quickly without having to wade through an amount of unfamiliar material. This approach is in the same spirit as the inheritance of properties in Smalltalk and other object oriented languages.

New Objects There is no provision in the current version of ELAB for the user to extend the number of Object classes or the various Object Properties. This is a defect which will be discussed in the next chapter.

Even with the current version some modelling of other interesting objects can be investigated. Ammeters can be thought of as resistors with a very low resistance but it is currently impossible to constrain the ammeter to function between certain current limits or to report back its 'deflection'. This means that, provided a student already knows how to model ammeters and voltmeters, there is no difficulty in asking questions involving such meters. On the other hand, it would be more desirable to offer a *Meter* class of which various meters were instances as there are educational advantages to learning the functionality of meters and then constructing a simple model.

The Circuit Analyser

The analysis is a fairly standard loop analysis which produces a steady state solution. That is, there is no attempt to find the transient response of the circuit. The solution provided for both DC and AC circuits assumes that only linear elements are used.

The current version of ELAB only allows one source of power in an AC circuit. This limitation can be easily fixed. A more difficult problem to fix is the limitation that batteries and AC sources cannot be mixed in the same circuit. A further assumption is that batteries only supply current at a constant voltage.

The decision to separate the circuit construction and the circuit analysis phases was prompted by parallels with building procedures and then debugging them. It would have been easy enough in principle to run the analyser each time the circuit topology or an object was changed. This would provide a great deal of quick feedback but it is believed that the separation of the two processes of building and running permits the student to face up to faulty beliefs in a more principled way. It also allows the student to go wildly wrong in that it might well prove extremely difficult to isolate the faulty decision among a number of decisions. This 'danger' is seen as an advantage but it will be necessary to give some further thought as to how the student can be encouraged to debug the circuit.

Topological Issues

Automatic Layout It might be thought that the student should not need to bother with exactly how objects are connected. It should be sufficient to declare that two objects are connected and the system ought to take care of the fine details.

Such an approach would require that the system handle both positioning of objects and how connections are drawn in.

It is a design principle, however, that as little as possible should happen on the screen which does not stem from the intentional activity of the student. The attempt to update the layout of a circuit as the student connects objects and creates objects would sometimes result in a number of visible effects which might not make immediate sense to the student. If we liken circuit building to doing a jigsaw puzzle then we might wish to take note that Skemp believes that unrequested interference can severely affect the motivation to complete the puzzle [Skemp 79].

The position that it is not the primary goal of the student to engage in moving circuit elements around the screen is appealing but, in some sense, the screen is the student's working memory. Therefore, the student should be in control of the circuit's representation. There is evidence, for example, that students do not easily identify two topologically equivalent circuits [Caillot 84, Johsua 84]. If decisions are taken by the system as to how to represent circuits then students may find that inappropriate or confusing decisions have been taken for them.

Making Connections Batteries, resistors and other electrical objects may be regarded as the nodes of a graph —which means that the arcs are the connections between them. The objects can also be seen as the arcs which are connected to nodes —provided that each object has exactly two terminals. It is quite clear, however, that both nodes and arcs have electrical properties.

In the first interpretation, the arcs are wires with two ends, a resistance (defaulted to zero) and, possibly, other properties while the nodes have to be expanded into objects which, in most cases, consist of two terminals and one of the predefined electrical objects. Yet two wires may join and it is usual to distinguish such a point. A *null* node is created wherever two wires meet. This node has a single electrical property. It has zero resistance.

The current version of ELAB does not permit the user to create an instance of the *Node* class in a direct manner.

It might be thought that wires used for connecting electrical objects are also first class electrical objects in their own right. Why maintain the current distinction? The simplest reply is that current educational practice requires that the student is introduced to circuits via *lumped* models of objects. It is, however, a reasonable requirement that the system should treat the connecting wires as first class objects. The issue as to whether the user interface should maintain the distinction could be investigated in a new version of ELAB.

5.6 Observations on ELAB Users

5.6.1 Observational Objectives

In section 4.5.1, there is a set of basic objectives underlying the use of DYNLAB. These objectives apply in much the same way to ELAB.

5.6.2 The Experimental Setup

Although the implementation of ELAB was incomplete in several ways of which some have been already outlined, it was thought advisable to gather some feedback from users of ELAB. The same local boys' school was used as in the previous observations in connection with DYNLAB. This school, Daniel Stewart's and Melville, was able to offer after-school sessions during the period January 1984 to March 1984.

As the observations were outside the normal school timetable, volunteers were obtained by the Head of Physics and selected in order that a spread of abilities was obtained —see appendix K for details of their physics performance. It is necessary to remember that the school used selects students for entry who are academically well above average.

As ELAB could be used to study circuits that are more complex than those in the normal 'O' grade syllabus it was hoped to use both students from S4 —prior to taking their 'O' grade in physics— and from S5. Four students from S4 and four from S5 were chosen for observation throughout the period. Two sessions were to be held each week —one for the four S4 students and the other for the S5 ones.

In all, about six sessions for each group[14] were planned as it was believed that this would enable them to finish the planned work. As it turned out, the volunteers were willing to attend extra sessions to finish the work. This was desirable as the DYNLAB observational sessions would have been far more revealing if more time had been available to see what the weaker students made of the harder modelling exercises.

Each student's work was split into four parts:

The Misconception Test: The students were all to be given forty minutes to answer ten questions selected from a number of sources of reported misconceptions in basic electrical theory. Each question was framed as a multiple choice question. The students were told that it was necessary to mark ANY statements that were correct and to try to give some form of explanation if possible.

An important criteria of selection was that each question posed a problem that could be modelled successfully using ELAB. The questions were slightly rephrased and put in a fairly arbitrary order —with the exception of two very similar questions which were kept together in order to assess the interference between them.

The function of the test was to provide some estimate of the nature of the student's models of electrical phenomena. This evidence proved useful when the students entered the construction phase.

The Introductory Phase: A period of ninety minutes was to be used to introduce the students to some of the features of the system. Six worksheets had been constructed to introduce the main features as quickly as possible. All but one of these worksheets presented the student with a complete

[14]Including the time for the misconception test.

circuit which needed modifying in a number of ways. Just one worksheet asked the student to build a circuit completely from scratch.

At this stage it was hoped that some of the software problems could be identified thus leaving more time for observation during the later phases.

The Construction Phase: A period of about three hours was originally planned to complete this phase. During this time students were to model all the circuits used in the misconception test —in whatever order they chose. All the students had time to model all ten problems although one or two evaded doing them all.

In general, the students worked through the problems in the same order as the problems appeared in the misconception test. Worksheets were provided to give quite explicit guidance to their work.

Initially, it had been felt that these (ten) worksheets might not really be needed at all and that the students could be left to their own devices. From initial observations of how most of the students tackled the problems it became apparent that even students in S5 could not reliably be left without some form of guidance in attempting to solve problems.

The Project Phase: The remainder of the available time was to be used to complete six very simple projects. Each project was accompanied by a worksheet which was distinctly less helpful than the ones accompanying the problems associated with the misconception phase.

The projects were chosen to be possible to solve with either principled methods or by means of some heuristic such as binary search. In the end, all the students volunteered to spend as much time as necessary to finish this phase completely.

A further four worksheets had been constructed and more planned to test ideas associated with AC circuits but little work was eventually done to explore the modelling and properties of AC circuits.

5.6.3 The Students' Background

There were two sources of information that were used to gather information about the general background of the students: a questionnaire completed by each of the students prior to the modelling with ELAB and a taped interview with their physics teachers. This latter source of information provided some information on the attitudes of the teachers involved as well as their programme for electrical circuit practicals.

The Questionnaire Summarised Broadly speaking, the students were provided with few opportunities to familiarise themselves with computer systems and concepts. Only two had been given computer studies classes at school and their programming experience seemed to be based on a few batch processed BASIC programs. Four of the students had some access to computers out of school hours but student A no longer used his Sinclair ZX-81 and student E only played the occasional computer game using a VIC-20. Student C had a BBC computer and student F had access to someone else's computer.

There is slight evidence that the more able students, as judged through physics exams and through their performance during the observations, had the greater 'hands-on' experience.

The students were also asked whether they saw computers as friendly or hostile. Their responses can be seen in table 5–3 with a grade of 0 indicating no hostility and 9 indicating maximum hostility. The other information relates to their perceived preferences for various types of computer usage. The rating is based on a grade of 0 indicating no interest and 9 indicating maximum interest. There is slight evidence that they saw games as the least interesting usage and a slight overall preference for applications programs suggesting that they saw the computer as a sophisticated pocket calculator.

Table 5–4 indicates the students' assessment of their own abilities as measured in terms of how difficult they see electrical circuits and practicals relative to

Student	Hostility	Play Games	Run Applications	Run CAI Programs	Write Programs
A	4.5	1	4	7	5
B	3	9	7	8	9
C	5	4	9	8	6
D	9	6	8	5	4
E	4	6	3	3	6
F	4.5	2	7	7	6
G	5	2	7	6	4
H	2	6	5	2	7

Table 5–3: Students' Attitudes to Computers

the whole of their physics work. This data is based on the answers to the questionnaire that the students filled in (appendix L).

Student	Circuits vs Physics	Practicals vs Physics
A	better	same
B	much worse	much worse
C	worse	same
D	much worse	same
E	worse	better
F	much worse	much better
G	worse	much better
H	worse	same

Table 5–4: Students' Perception of their Abilities

Table 5–5 indicates the students' assessment of how they felt that their physics teacher estimated their abilities. Again, this is measured in terms of how difficult they saw electrical circuits and practicals relative to the whole of their physics work. Roughly speaking, students A, B, D and F believed that their teacher overated their physics performance. Student D's teacher regarded him as confused in practicals because he was probably confused at the theoretical level while student B's teacher believed he was able but not an initiator in practical sessions.

Student	Circuits vs Physics	Practicals vs Physics
A	same	better
B	same	same
C	same	same
D	same	same
E	worse	same
F	much worse	much better
G	worse	much better
H	worse	much worse

Table 5–5: Students' Perception of Teacher's Estimation of their Abilities

Student C believed that his teacher underestimated his abilities which is interesting since his teacher believed that he had, despite him being the most able of the S4 students according the the school's physics records, too high an opinion of his abilities. Student E only thought that the teacher was over-generous about his practical ability. Students G and H believed that their teacher overestimated their ability at the academic aspects of physics but underestimated their practical ability.

Their teachers were reluctant to attempt an estimate of their abilities for a number of reasons. For example, it was considered extremely difficult to make detailed observations about the attributes of individual students in respect of their practical work.

The Teaching of Electricity The basic program of practical work starts with some simple electrostatics experiments. There is some experimental work based around Ohm's law but no attempt to explore the series and parallel addition of resistances. They go on to build a motor.

The circuit work, for at least one teacher, starts with a bulb and batteries in series then in parallel. Ammeters are used to find the current at various points of the circuit. This work is repeated to investigate voltages. Ohm's law is investigated and is most satisfying in that the experiment tends to produce an excellent straight line through the origin. The heating effect may be explored through the use of bulbs. Finally, power is explored through the use of the same simple circuits involving batteries and bulbs.

There is a marked reluctance to teach any electrical concepts by analogy with the fluid flow analogy. All the teachers interviewed seem to prefer the particulate model. Once, the Scottish physics syllabus encouraged the continuous view strongly by including material on heat, electrical and water flow. Now, the emphasis in the syllabus is on the side of the particulate model, one reason for why the teachers interviewed preferred the particulate viewpoint.

Nevertheless, the teaching styles are quite different according to the teacher's own perceptions. One teacher treats circuit analysis as a (more or less) formal discipline. Terms such as "V" may well be uninterpreted. Another teacher tends to introduce the 'moving crowd' model as the basic electrical model. His models include crowds leaving football grounds and 'traffic circuits'. His main concern is to present a clear picture; he does not worry unduly about the models that the students actually possess. A third teacher is concerned to develop the qualitative reasoning abilities of the students.

5.6.4 The Misconception Test

The Design of the Test

Ten questions were selected from those described in the literature. Of these, the first two were selected from Johnstone and Mughol's paper [Johnstone & Mughol 78]. The remainder were selected from the paper by Cohen, Eylon and Ganiel [Cohen et al 83]. Some changes were made to make the questions slightly less abstract and a little more tractable for modelling by the students during the construction phase.

The Application of the Test

The misconception test was applied before the students began their work with ELAB. A time of forty minutes was given for the test. The students were explicitly informed at the start that it was not necessarily the case that there was one and only one answer. They were also asked to provide as full an account of their answers as they were able.

What is the Test Testing?

The misconception test does not test the student's ability to do complex algebraic or numeric manipulation. Very little formal algebraic or arithmetic manipulation is possible. On the whole, the students are required to think in terms of relations between quantities.

Nor does the test examine the ability of the students to run some 'analogical' simulation of the circuits although there are opportunities to do so. There is also some evidence that this actually happened.

A careful analysis of the test reveals that some questions require a much deeper analysis than others. Table 5-6 below shows a crude estimate of the number of propositions that have to be known and deductions that have to be made in order to get each question completely correct. This includes deducing which options are correct and reasoning why the remaining ones are incorrect. A deduction may be the recognition of a logical contradiction, a deduction from the currently available data and so on.

The determination as to exactly how many such steps is involved will depend crucially upon what each student knows. It is therefore quite hard to pursue this approach much further though there is a very rough correlation between the number of reasoning steps and the difficulty of the questions as measured in terms of the number of correct answers obtained.

Perhaps the main issue is the nature of the misconceptions that are to be tested.

Question	Number of Basic Facts	Number of Deductions
1	2	5
2	2	2
3	5	5
4	4	5
5	5	4
6	3	5
7	1	6
8	4	5
9	3	6
10	5	5

Table 5–6: Estimates of the Complexity of the Misconception Test

An Overview of the Misconception Test

At a global level, there were twenty-seven completely correct responses out of a maximum of eighty. Table 5–7 gives a comparison between the results obtained for the misconception test and the results obtained through circuit modelling for the eight students. This is combined with the number of sessions required to go through the whole programme of work.

Student	Number of Correct Decisions in the Test	Number of Correct Decisions During Construction	Number of Sessions
A	4	7	5
B	2	5.5	8
C	5	9.5	6
D	4.5	5.5	7
E	3	6	5
F	4	7.5	6
G	0.5	3	6
H	4	6.5	5

Table 5–7: Performance of Students using ELAB

The results suggest that there is a very strong correlation between success in the Misconception Test and success during the Construction Phase —especially if student D's results are ignored. His results were good for the test but his performance during the Construction Phase was relatively poor. Table 5–8 gives a simple overview of the results obtained. In the following question-by-question

	Student Identifier								
Question Number	A	B	C	D	E	F	G	H	Number Correct
1	c	a/d	c	c/d	a	c	d	c	4.5
2	a	b	a	a	a	a	b	a	6
3	b	a/b	a	-	b	b	a	a	0
4	a	b	b	d	a	d	b	c	2
5	c	a/d	d	a	c	a	a	a	1.5
6	c	c	a	a	c	d	c	a	3
7	c	b/c	a	b/d	d	b	b	c	2.5
8	d	a/b	b	a	b	c	c/d	c	2.5
9	c	b/d	c	c	d	d	c/d	a	3
10	d	a/b	c	d	c	c	c	c	2
Number Correct	4	2	5	4.5	3	4	0.5	4	27

1. Correct choices are emboldened

2. A correct choice given with another incorrect choice is counted 0.5

Table 5–8: Misconception Test Results

analysis the range of potential misconceptions becomes much clearer. Some of these misconceptions can be directly inferred from the students' own written answers and others are suggested by an analysis based on the answers of the students.

Question 1

This would seem to be a very straightforward factual recall question (see figure 5–5). Nevertheless only four students out of eight produced a completely correct response. That is, selected option c) as correct and stated that the other three were incorrect.

The clue to the popularity of this option may well lie in a context trigger —the word *parallel*. Students may associate the concept of *equality of potential differences* with the trigger word *parallel*.

1. The two appliances are wired to the mains parallel with each other so that they may have the same

a) Current in them

b) Operating temperature

c) Voltage across them

d) Power supplied to them

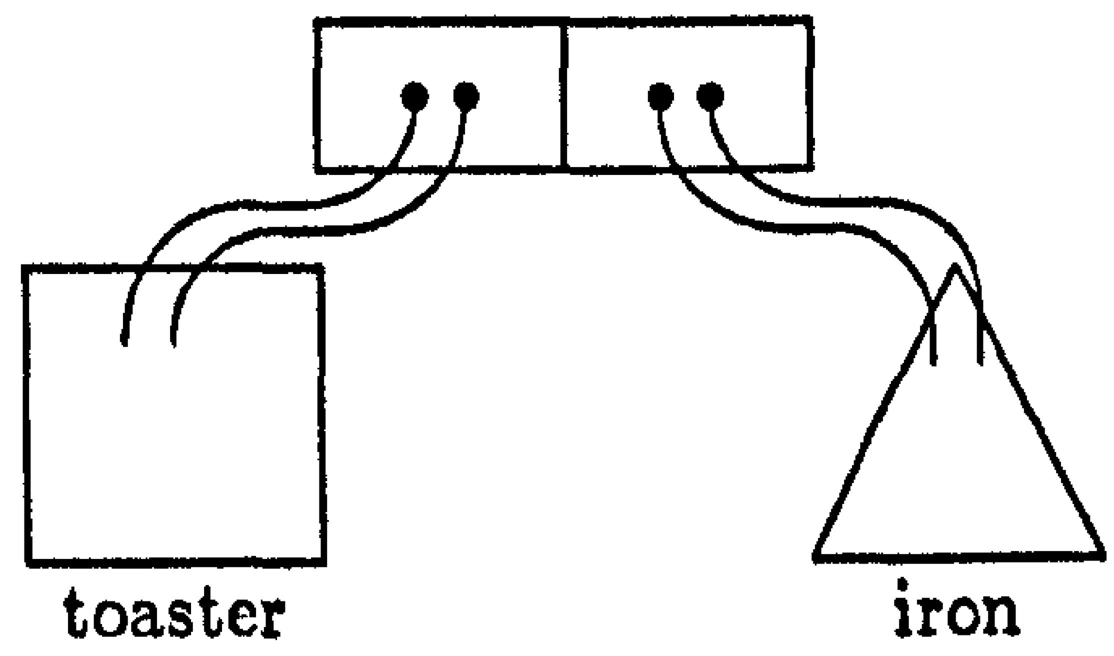


Figure 5–5: ELAB Question 1

The most popular misconception seemed to be that the functional requirement for the Iron and Toaster was that they should have identical currents. This suggests the belief that the objects are wired in series. Although the students should have realised that the objects were wired in parallel, the diagram does not indicate a clear *prototypical* instance of two objects wired in parallel. It is easy enough to interpret the diagram so that the toaster and iron are wired in series.

An alternative account of why some students opted for choice a) is that they may believe that devices require certain currents to flow and that if a device needs a current then it draws it. This might be given the name *wants-current—gets-current*. Such a misconception is an instantiation of a class of misconceptions along the lines that "if a device wants or needs a certain amount of X to work properly then it gets that amount of X".

Of the options proffered, b) proved unpopular and, although offering a plausible function for electricity in the case of the objects (iron and toaster), the students seemed to realise that the argument did not generalise.

Option d) would seem to be more plausible. Certainly Johnstone and Mughol claim that this option is the most 'powerful' distractor. Students are often informed that electrical energy can be converted to other forms —including mechanical energy. Here, we may have an instance of the misconception *wants-power—gets-power*.

Question 2

2. A student wishes to bridge the gap between X and Y so that the bulb may glow as brightly as possible. He should use a

a) Short thick conductor

b) Short thin conductor

c) Long thick conductor

d) Long thin conductor

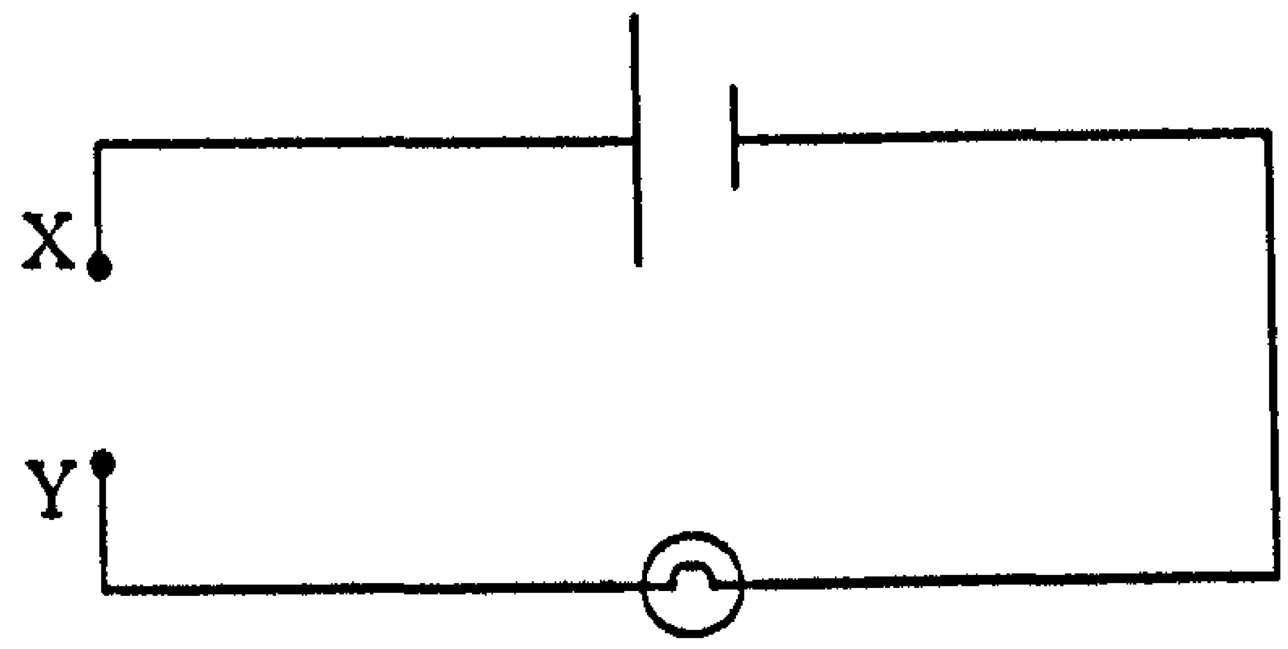


Figure 5–6: ELAB Question 2

This question (see figure 5–6) is also taken from the paper by Johnstone and Mughol [Johnstone & Mughol 78].

It was the easiest question with six correct responses although two of these six initially chose the short thin conductor. Table 5–6 suggests that this question is the 'easiest' in terms of the number of facts and deductions involved.

Student F stated that he only realised his mistake after solving question 10. Student A gave the clearest explanation of a correct choice which involved "giving the electrons plenty of space to move over a short distance".

The two wrong responses were for the short thin conductor emphasising the known tendency for students to associate a small 'measure' with a small resistance. One can see this as an appeal to the general (non-electrical) principle that diSessa refers to as the Ohm's law p-prim [diSessa 83]. The 'bug' is the misconception *more material—more resistance.*

Question 3

No one got the question in figure 5–7 right. The wrong answers were evenly divided between the first two choices.

3. A battery is connected to two resistors R and r in series. An additional resistance R′ is connected, in parallel with R, between N and M. Consequently:

a) The current through r does not change, and the currents in R and R′ are inversely proportional to their resistances.

b) The p.d. between M and N does not change.

c) The current through r increases and the p.d. between M and N decreases.

d) The heat developed in R does not change.

e) The current through r increases and the p.d. between M and N increases.

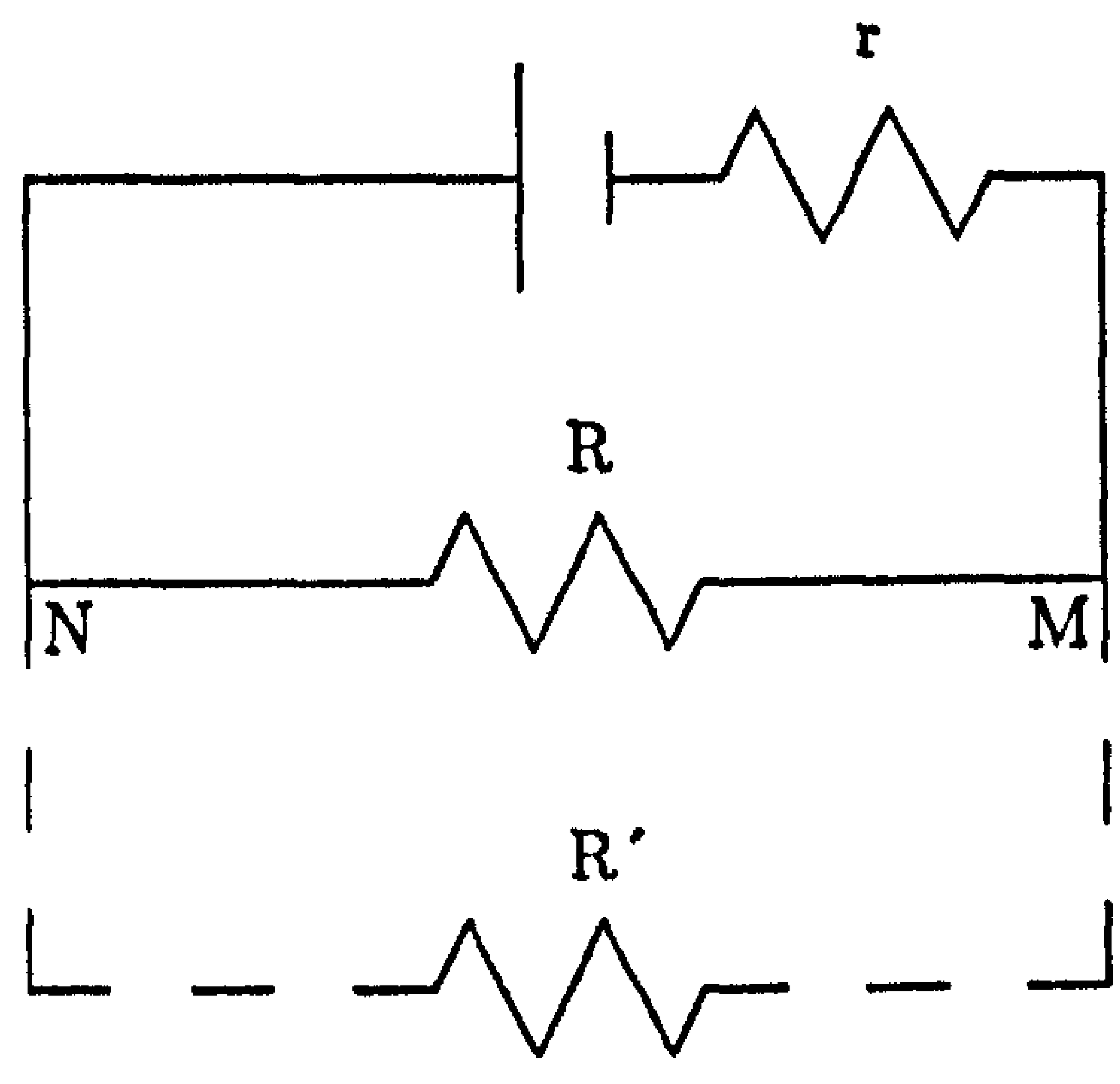


Figure 5–7: ELAB Question 3

The first choice is interesting in that the second part of the option is often taught (correctly) as a quite general rule. It could be that the student is uncertain about all the statements and chooses the first option because they know that the second part is right. Alternatively, to make this choice the student may have believed that the total resistance in the circuit has not changed —but how is this conclusion reached? Cohen, Eylon and Ganiel suggest that the thinking behind this choice is the belief that the battery provides a constant current. This is named here as the *battery-supplies-constant-current* misconception.

The most plausible assumption may well be the belief that no changes take place to the quantities input to —or output from— the 'primary focus'. In this question, the primary focus is the slice which incorporates the part of the circuit which is initially resistor R and then becomes two parallel resistors. This possible belief is named the *no-changes-outside-primary-focus* misconception will occasionally be abbreviated to NCOPF from now on. From this belief the student is able to deduce that the battery does supply a constant current.

So there are two clear contenders for a single misconception that can (partially) account for the choice of option a) or option b). There is one more for option b). Student E stated that the PD across MN "is unaffected by the added resistor as it is added in parallel". Is he simply ignoring the existence of the resistor r? It is possible that this is the case but it is also possible that he believes that he knows an applicable rule. Is this some wrong deduction from the statement that the PD is the same for all parallel branches however many branches there are?

A model of how students actually attempt to solve such a problem might require that the student possesses a set of rules which are triggered by focussing on specific parts of the circuit. The student would focus on some part of the network initially and try to invoke some rule/fact. If this proved too difficult then another point would be selected. Once a suitable conclusion has been reached then other foci are tried until no further fact/rules are invoked. It may then be possible to model the student's inability to reason deeply enough in terms of some accumulating processing cost. The user model would then be a set of rules and facts together with the associated cost of processing the facts/rules. This cost may well depend on the complexity of both the inputs to (and outputs from) the facts/rules.

Question 4

4. The electricity supply to our homes is a voltage source of 240V. Two light bulbs are connected to this source in series. Both are designed for use with the domestic voltage, one for 15W and the other for 150W. Consequently:

a) The 15W bulb will burn out.

b) The 15W bulb will light dimly, the 150W bulb will light strongly.

c) Both bulbs will light dimly.

d) The 15W bulb will light almost normally while the 150W bulb will hardly light at all.

Figure 5–8: ELAB Question 4

There were two correct answers to the question in figure 5–8, with the most popular incorrect response being that the 15W bulb will burn dimly while the 150W bulb will burn strongly. This choice might be explained on the assumption of mainly sound reasoning with a single bug —that the bigger the 'wattage' of the bulb the bigger the resistance. The student can then reason quite plausibly to the faulty conclusion.

Nevertheless, there are other possibilities. For example, the misconception *wants-power—gets-power* might be a contender but it seems to apply to each of the bulbs. This means that a further assumption is needed. For example, if X_i units of some quantity is wanted by consumer_i then the single producer produces ΣX_i units of the quantity. This would lead to both bulbs being lit fully. Now suppose that the producers only listen to the greatest request. The producer generates $\max(X_i)$ units. Now, a principle is needed to determine how the consumers negotiate for limited sources. A natural one would be that the greedier consumer gets the bigger share. This would lead to the bigger bulb lighting almost normally and the smaller bulb lighting very dimly. Unfortunately, this 'misconception' requires three separate misconceptions to be combined.

Another interesting choice is the belief that the 15W bulb blows up. This choice seems to be based on the assumption that there is a 'flow' of power round the circuit and that each object draws its required wattage. The battery duly sends round the correct wattage but the 15W bulb cannot take this.

The (correct) belief that the 15W bulb is bright while the 150W bulb is dim may be based on a flow of power with each bulb as a gate. The 15W bulb, being the smaller gate, simply does not let enough power through to light the 150W bulb —but the 15W bulb is bright!

Only one student believed that both bulbs would be dim.

Question 5

Only one person produced the right answer to the question in figure 5–9, with most of the others going for M lighting more strongly. This latter choice can

5. The voltage source E in the figure has no internal resistance. Both bulbs M and N are lit. N is replaced by a bulb with a much larger resistance. Consequently:

a) The bulb M will light more strongly.

b) The p.d. across N will become almost zero.

c) The p.d. across N will not change.

d) The p.d. across N will increase.

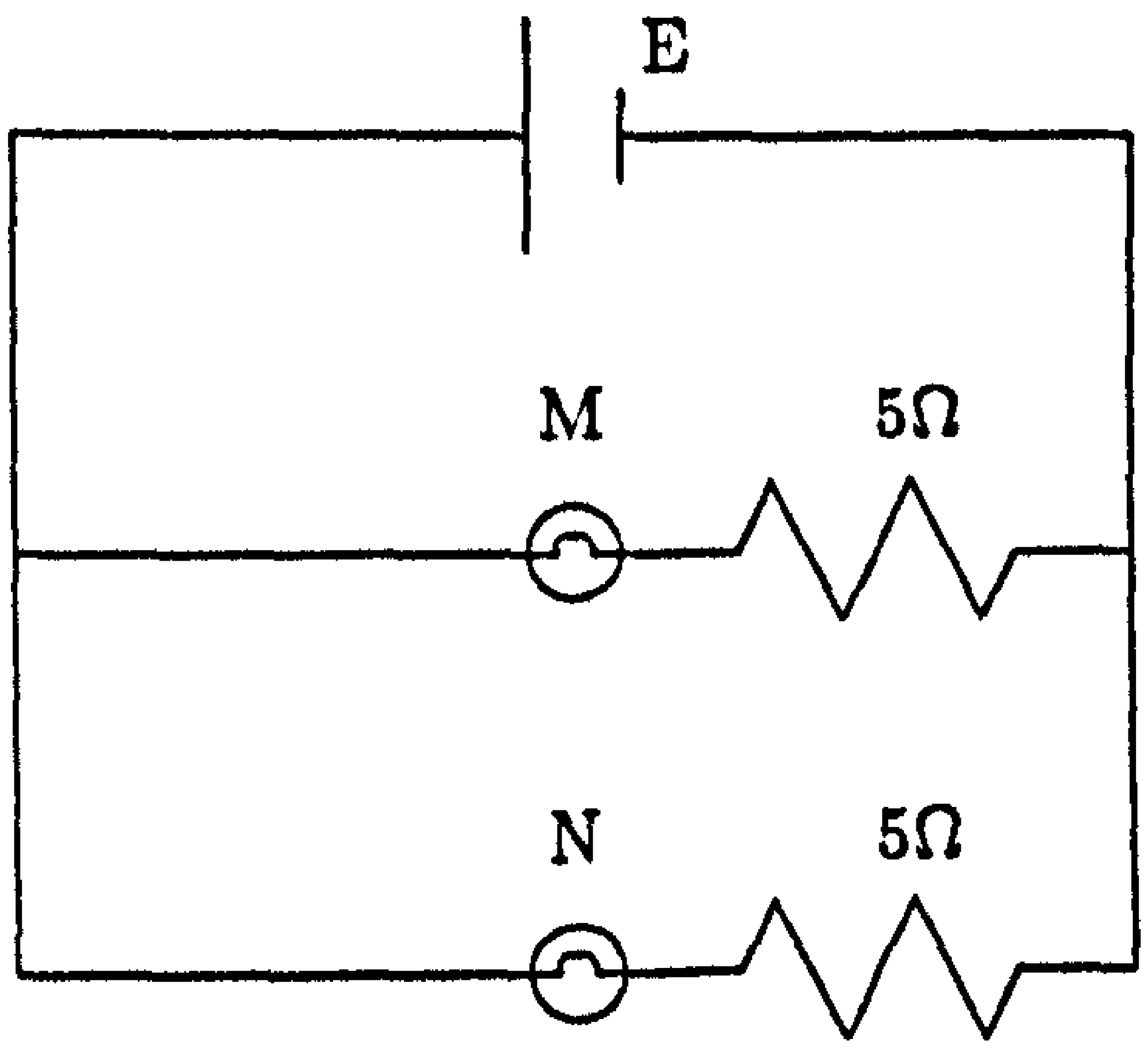


Figure 5–9: ELAB Question 5

be seen as another example of the *no-changes-outside-primary-focus* misconception. Students are trained to recognise such circuits as 'parallel' which creates a primary focus based on the two parallel arms of the circuit between M and N. Student G described the circuit as having "resistors in parallel with bulbs" He correctly stated that as the resistance of one bulb goes up so the total resistance goes up *slightly*. Taking his statement literally, if the resistors were both on one arm and both bulbs on a parallel arm then the brightness of bulb M would drop. If the circuit is redrawn so that the bulbs are in parallel and the resistors also in parallel then the brightness of bulb M increases. Now it is very difficult to determine from the evidence whether the student has reconstructed the circuit with a different topology but there is a principle here that would have to be taken into account by any tutorial program. That is, even if the circuit diagram is in front of the student, the student may have a different circuit in mind. Thus it may be necessary to search through various possible reinterpretations of the circuit to find one in which the student's belief about the circuit's behaviour is closer to the actual behaviour.

Student D chose both the correct option and option a). This seems to be a combination of the *no-changes-outside-primary-focus* (NCOPF) misconception with, as it happens, a correct analysis for the redistribution of PD for resistors in series. It may well be that the NCOPF misconception also applied as, having dealt with the primary focus associated with the two parallel arms, the student may have refocussed on the single arm including the bulb N.

It may be that, since the focus of the question is upon lit bulbs, the question triggers a model of batteries that supply as much power as they are able; since it is now harder to supply one part of the circuit the battery can now deliver a larger share of its power across M and the series resistance. Therefore the bulb glows more brightly.

Question 6

6. The voltage source E in the figure has no internal resistance, and both bulbs M and N are lit. N is replaced by a bulb with a much higher resistance. Consequently:

a) The bulb M will light more strongly.

b) The p.d. across N will become almost zero.

c) The p.d. across N will not change.

d) The p.d. across N will decrease.

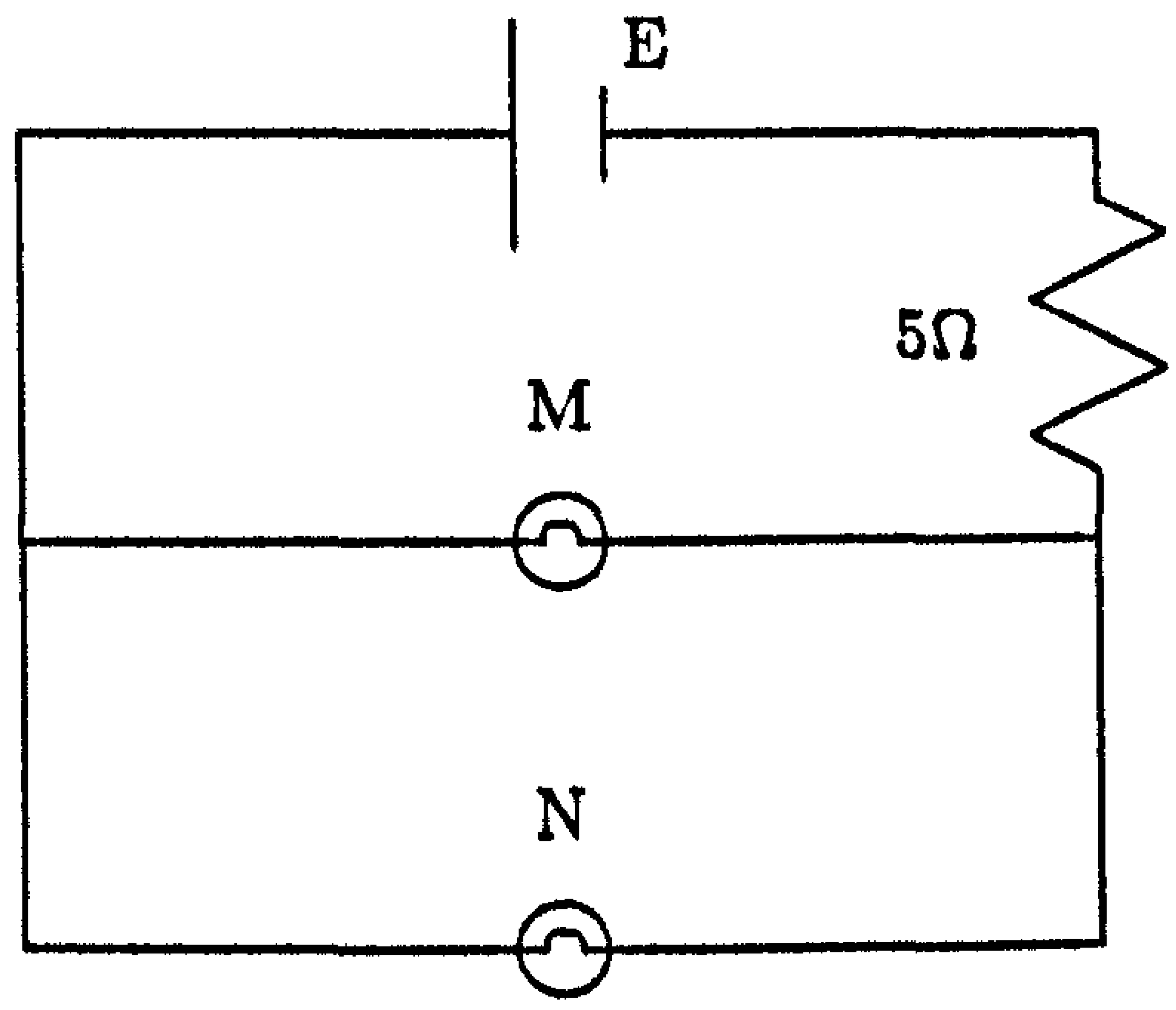


Figure 5–10: ELAB Question 6

Three people got the right answer to the question in figure 5–10 but it is unclear as to whether they knew why it was the correct one. Certainly one confessed to guessing and three stated that they could see no difference between this question and the preceding one. Even so, four thought the p.d. across N would not change. This is plausible if the resistance in series to the battery is ignored.

Why do students believe the two circuits are the same? There are at least two possible explanations:

- Students match two circuits as identical if
  - the topologies are identical; all objects being regarded as indistinguishable
  - if there is a 1-1 match between objects.
- Students see the circuit in question as two circuits overlaid. See figure 5–11. This might be termed the *circuit-overlay* misconception.

Initially, the most convincing is the first account —except that there is not a 1-1 match between objects.

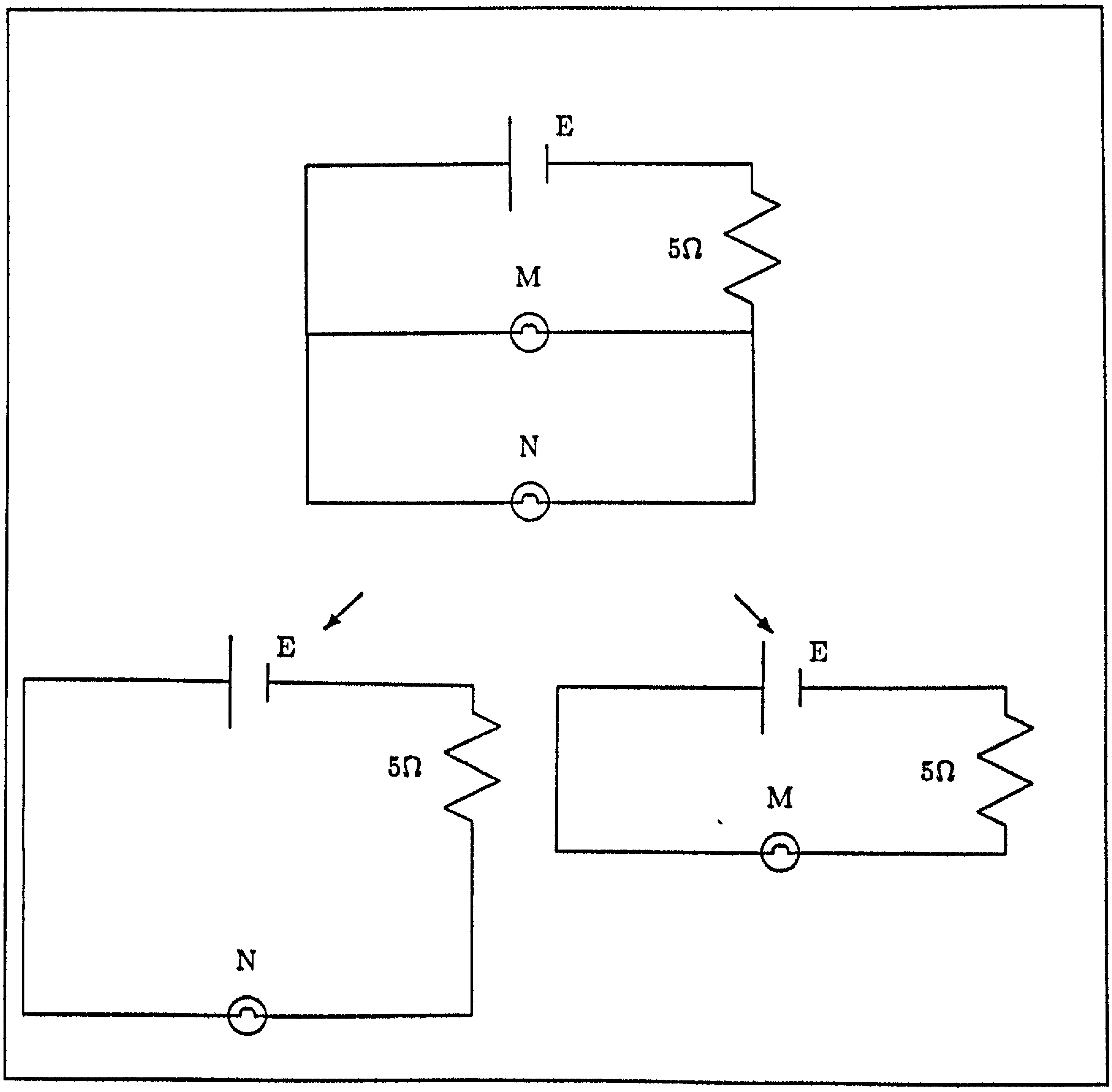


Figure 5–11: A Circuit 'Split' into Two

Question 7

7. The battery in the figure has no internal resistance. A second battery, ***identical*** to the first, is connected in parallel to it, as indicated in the drawing. Consequently:

a) The current through R will increase.

b) The p.d. across the resistor R will increase.

c) The current flowing through the first battery will decrease.

d) The current flowing through the first battery will not change.

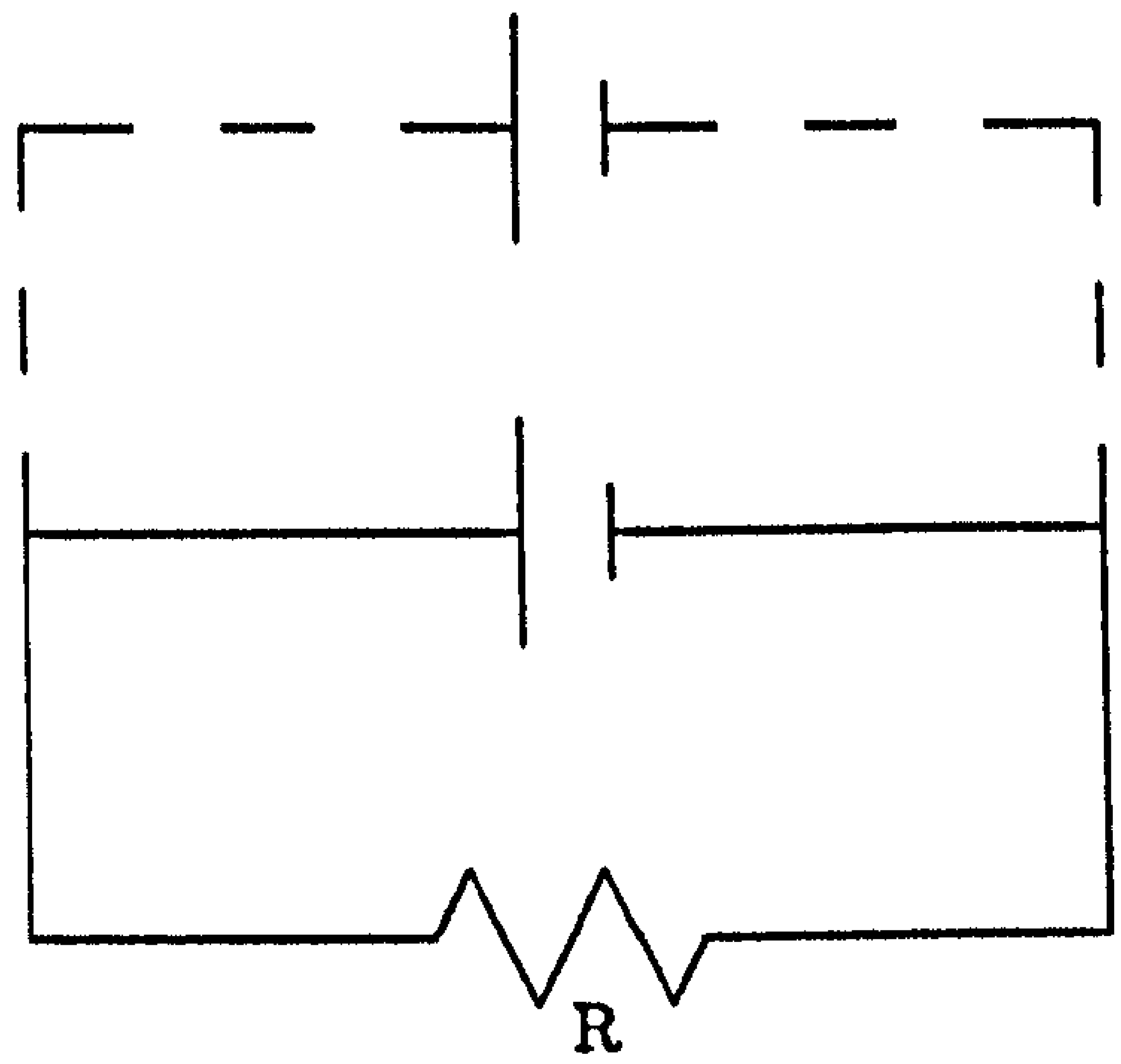


Figure 5–12: ELAB Question 7

This question (see figure 5–12) was a modification of one found in Cohen's paper [Cohen et al 83]. The original had featured an ammeter but all reference to this was dropped to reduce the number of objects about which to reason. There were two correct responses, with the most popular choice being that the PD across R would increase. Looking at table 5–6 it would appear that the correct answer depends critically upon one central fact which is that two batteries in parallel have the same PD as one.

The most popular wrong answer ties in nicely with a false generalisation about the way batteries behave. If the student knows that batteries in series add their PDs then deduces that batteries in parallel do the same —a plausible but incorrect inference. This is the *more-batteries—more-PD* misconception which can be seen as another example of the Ohm's Law p-prim.

The belief that the current flowing through the initial battery does not change is consistent with the *circuit-overlay* misconception.

It is possible that some student could reach the correct answer by an analogical argument.

$$\left.\begin{array}{lll} \textit{resistor} & \textit{main property} & \textit{resistance} \\ \textit{battery} & \textit{main property} & EMF \end{array}\right\} \begin{array}{l}\text{add another identical in parallel}\\ \Rightarrow \text{halve value of main property}\end{array}$$

This argument, illustrated above, needs to be supplemented by two more rules:

- The value of the PD across the battery equals the value of the EMF it supplies
- If the overall value of the PD goes down then the current delivered by the battery must go down
- If the total current goes down then the contribution of the original battery must decrease

The correct choice can now be made.

Question 8

8. In the circuit drawn in the figure, the ammeter has no resistance, and the battery has an e.m.f. E and an internal resistance r. Which of the following is correct?

a) The current flowing through the ammeter is zero.

b) The p.d. across the ammeter is zero.

c) The potential drop *inside* the battery is zero.

d) The energy dissipated in the whole circuit is zero.

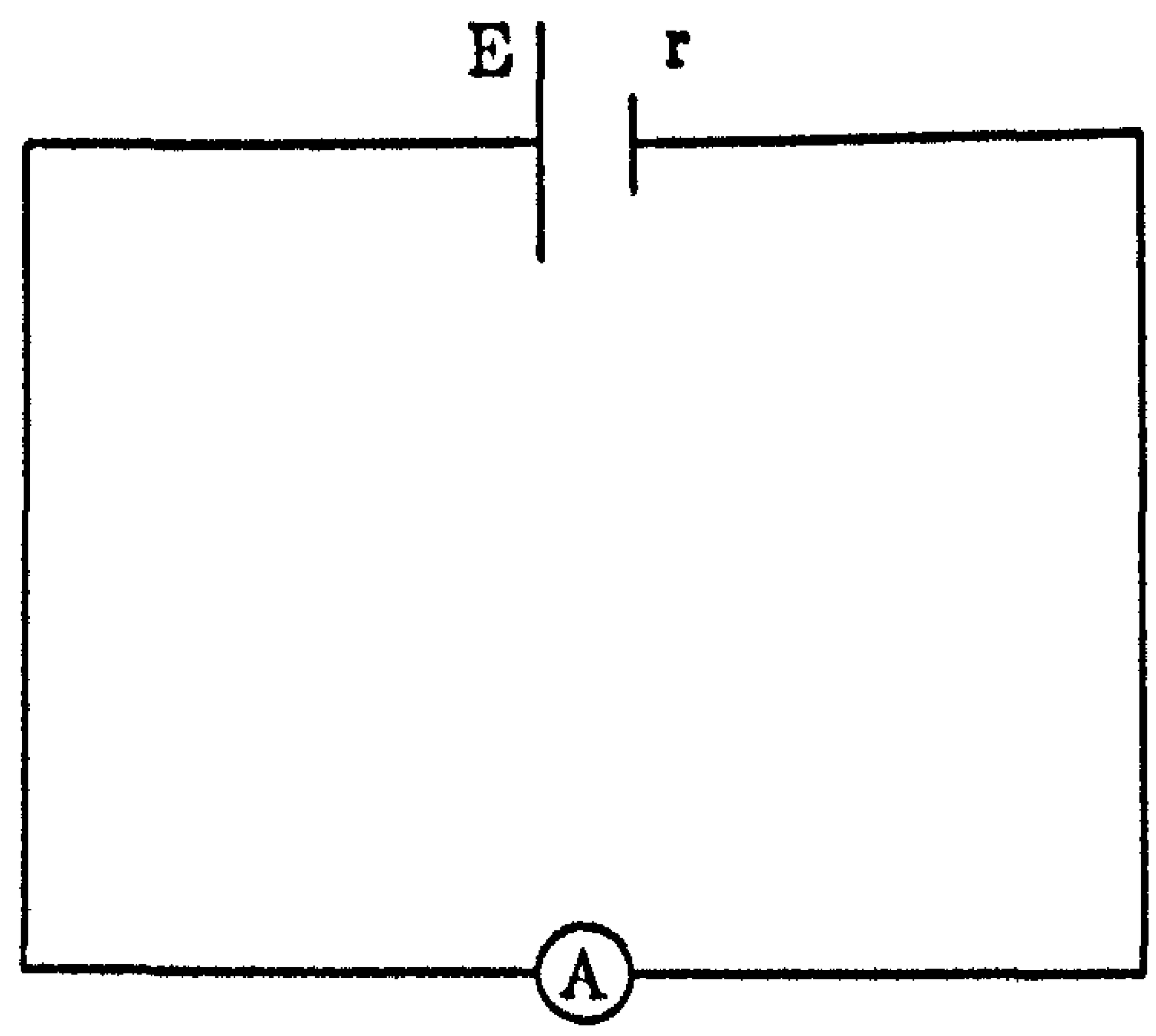


Figure 5–13: ELAB Question 8

There were three correct responses —see figure 5–13— with the rest divided almost equally between the other three possible answers. This seems to be a hard question because it requires the student to know something about what goes on inside the battery and about circuits. Nevertheless, some misconceptions can be deduced. One such is the *no-resistance—no-current* bug. Student B chose options a) and b) which is consistent with this.

Student A stated that "current runs in a ring so nothing given off". This is suggestive of the belief that current is consumed by resistors with a non-zero resistance.

Question 9

9. A resistor R is connected in series to a source which has no internal resistance. A second resistor, identical to the first, is connected to it in series. Consequently:

a) The p.d. between the terminals of the battery increases.

b) The p.d. between the terminals of the battery decreases.

c) The rate of heat dissipation, in the two resistors together, is *double* the rate at which heat was dissipated previously in the single resistor.

d) The rate of heat dissipation, in the two resistors together, is *half* the rate at which heat was dissipated previously in the single resistor.

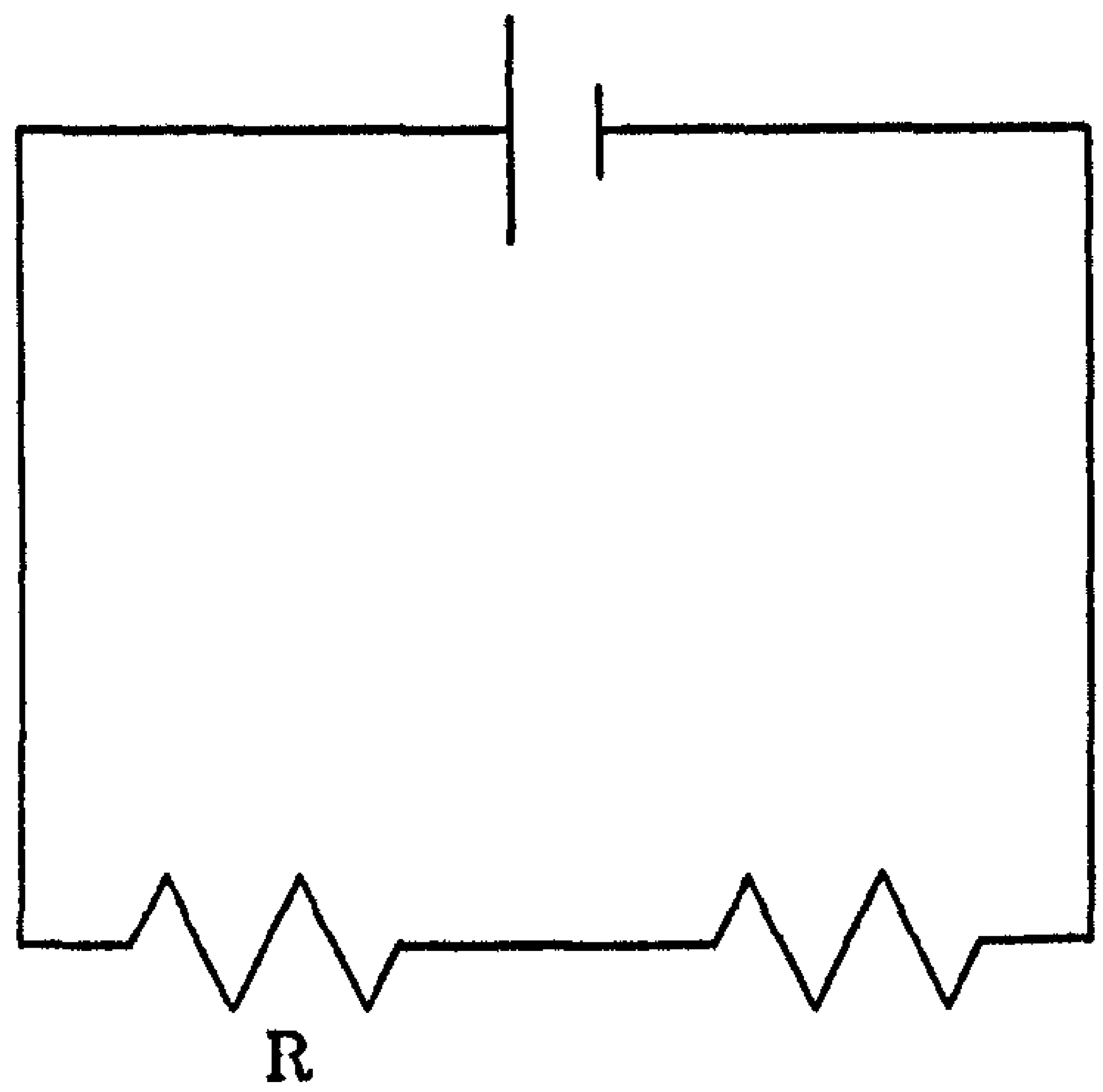


Figure 5–14: ELAB Question 9

There were three correct answers, with three others stating that the heating effect doubled —see figure 5–14. This can be accounted for by the Ohm's law p-prim *more-X—more-Y* for two (possibly connected) quantities. An alternative account is the *no-changes-outside-primary-focus* misconception which leads to the belief that the current through the two resistors does not change. A correct application of Ohm's law then indicates that the PD does not change for either object. By the law $P = IV$, it is now possible to see that the power output for the original resistor does not change. Thus it is possible to deduce that the heating effect doubles.

It is difficult to understand how two people might be led to believe that the PD across the battery increases! There is, however, an explanation. If batteries always deliver a constant current and if the resistance of the circuit has doubled then the PD across the total circuit has doubled —according to Ohm's law.

Question 10

10.A resistor is connected, through an ammeter, to a battery which has an e.m.f. of 10 Volts and an internal resistance of 2 Ohms —see figure. Now the points M and N are connected using a short thick piece of copper wire. Consequently:

a) The current flowing through R does not change significantly.

b) The current flowing through the copper wire is very small because the p.d. across it is very small.

c) The current flowing through the ammeter does not change but the current in the circuit flows mainly through the copper wire.

d) The current flowing through the ammeter increases and most of the current in the circuit flows through the copper wire.

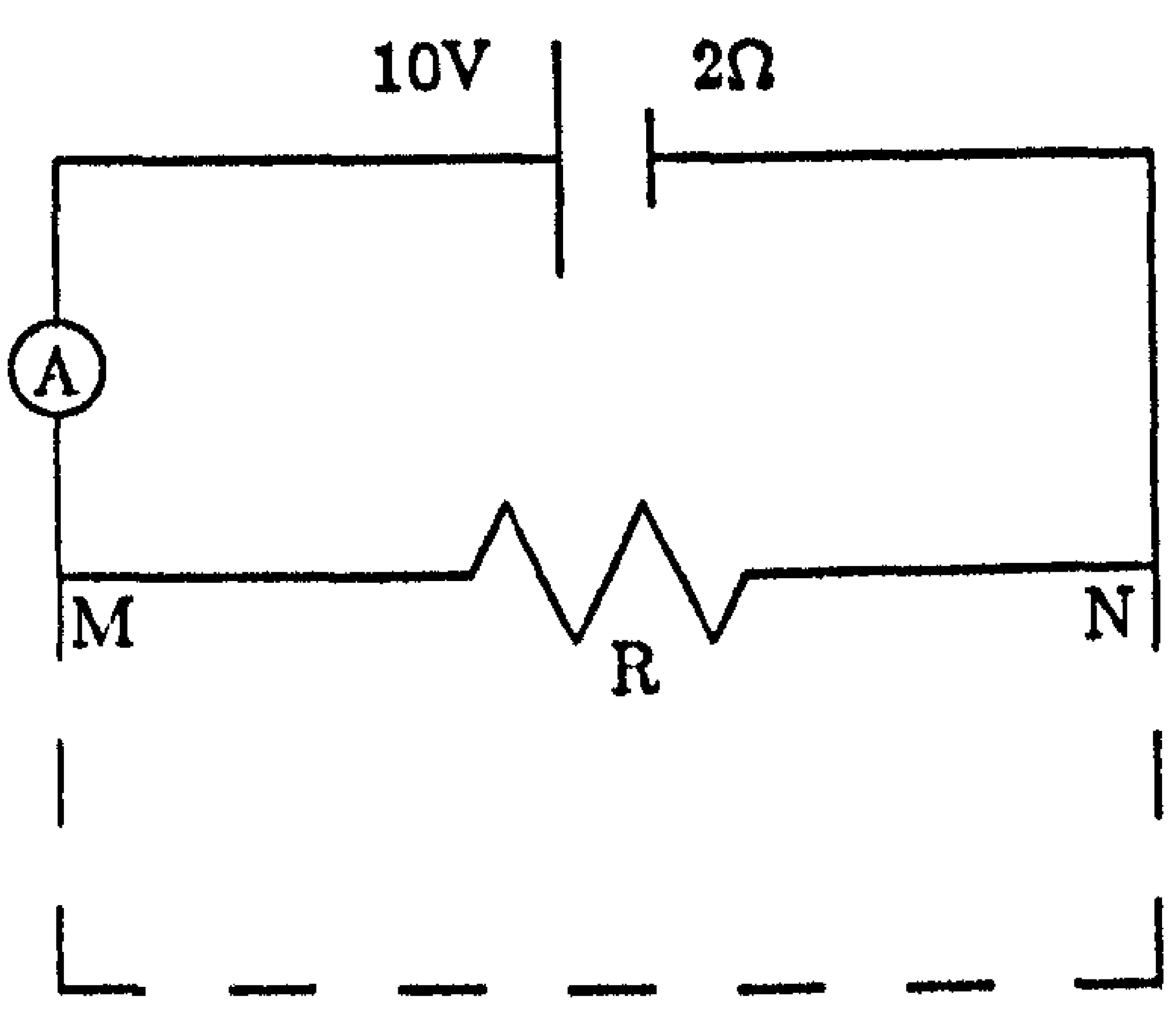


Figure 5–15: ELAB Question 10

There were two correct responses, and five others going for the current in the ammeter not changing —see figure 5–15. The choice of option c) seems a clear case of the *no-changes-outside-primary-focus* misconception. One student crossed out the correct answer in favour of this choice.

Student B, the only one not accounted for, chose both option a) and b). This is consistent with the view that if an object has no resistance then there can be no current flow through that object.

5.6.5 The Observations

The misconception test yielded some data on the possible beliefs that the student had about the behaviour of electrical components and relationships between electrical properties. The observational period provided the opportunity to determine whether the use of ELAB threw any light on the problems that the students had. A plausible initial assumption is that the students use the same set of assumptions and methods of reasoning during the construction phase as they used during the misconception test.

Further, there was an opportunity to assess the problems that the students had with the modelling of circuits. This has two aspects: the modelling process *per se* and the user interface which ELAB provided.

The data for the observations was obtained in a number of ways:

- Written notes taken during work sessions
- Worksheets filled out by students
- Dribble files of each work session
- Audio tapes of work sessions
- Questionnaire given to the students
- Interviews with teachers

The data obtained by means of any one of these methods could not provide a sufficiently detailed picture of the students' progress. Apart from any theoretical reasons as to why this is the case there were the inevitable practical difficulties in obtaining fully completed worksheets and clear audio recordings. In addition, throughout the observational period the hardware proved to be extremely fragile. This led to the loss of some dribble file data and increased management problems.

An Overview

In all, the eight students were required to work through a total of twenty two worksheets grouped into three types. First, a set of introductory worksheets then worksheets for the construction phase, and finally, a set of worksheets for the project phase.

The Introductory Phase

The introductory material consisted of six worksheets. The complete set was designed to take the student once through the main features of ELAB. The design was based on the principle that a minimal understanding of the basic ideas/skills should be provided. This was then progressively expanded in such a way that the more fundamental skills were met first.

Worksheet	Concepts/Skills
1	Choose a circuit, run the analyser and quit
2	Examine and change property values and then save the new circuit
3	Display various property values
4	Create a circuit, create and place an object and then wire up
5	Unwire an object and destroy an object
6	Swap two objects, turn an object around and move an object

The following is a summary of the observations that reflect on the students' progress through the six worksheets.

Typing 'at' the Wrong Object The only time the student is required to type is when a value for a property is required. This means that the student has to have specified the object and the property. Student G tried to set a resistor's resistance to 23Ω. He should have first selected the name of the object from the appropriate menu, the property to be changed and only then type in the new value. He *typed* in the name of the object "res1" in the following contexts:

1. Just before choosing the command to set
2. Just after choosing the command to set but before moving the cursor to point at the object named "res1"
3. Just before choosing the object named "res1"

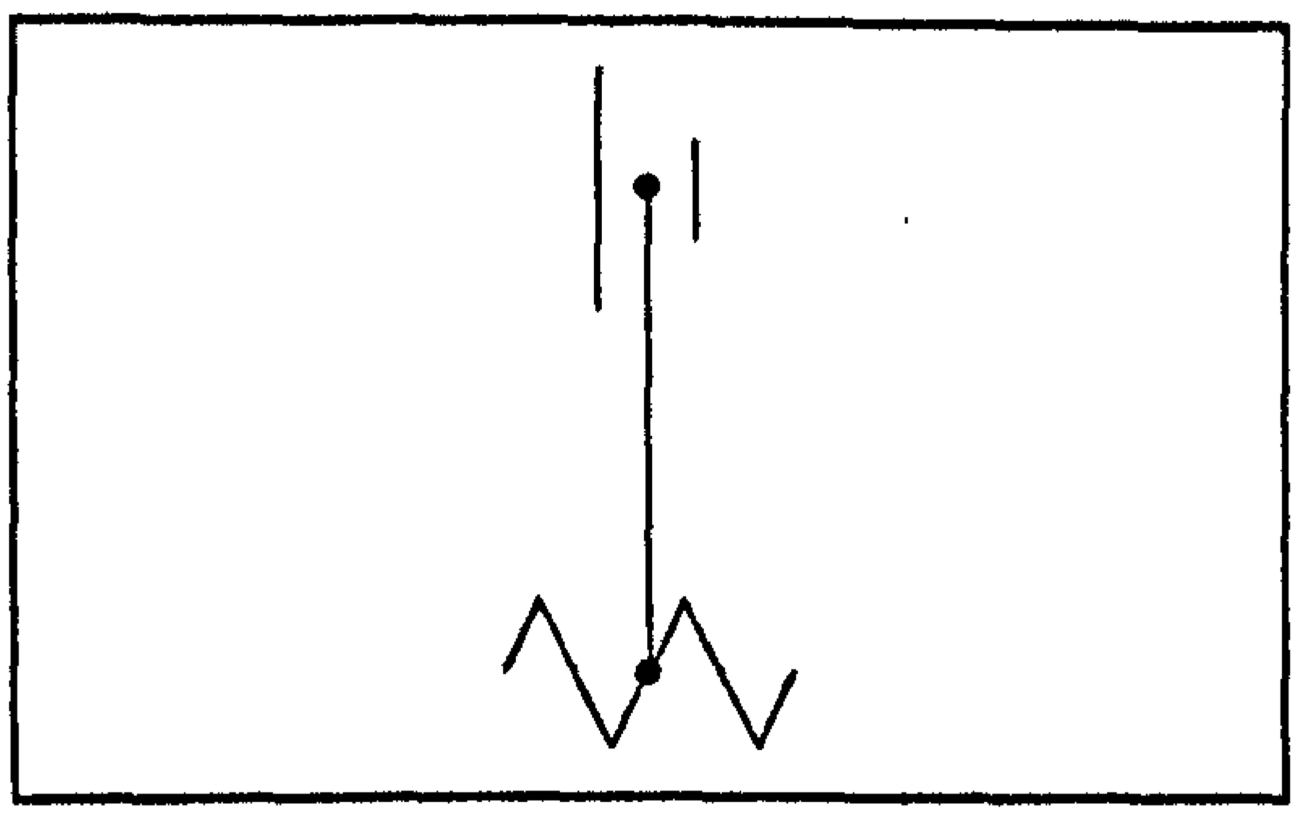
Related behaviour by student B involved trying to select the display of "V/I" by typing "V/I" after issuing the command display. All he needed to do was use the RETURN key.

A different error lies at the root of the behaviour of student D who tried to type in the battery's EMF without specifying that the value was to be associated with the battery's property of possessing an EMF. He seemed to believe that ELAB should realise what he meant.

Mistaken Observations Inevitably, there were situations in which an item was misread. This may well be due to a simple performance slip such as the case where students F and G failed to notice the position of a decimal point correctly. On the other hand, some misreadings are possibly symptomatic of an incomplete concept. For example, student G failed to observe that a battery dissipated a *negative* amount of power. There is also some evidence that the students did not readily interpret directions assigned to currents and potential differences.

The Idea of Wiring Up Student H mistook the command wire for the object class '(thin) wire'. Student E tried to place a 'thin wire' on top of the battery in attempting to wire up a circuit. Student F tried to do the same. Then he tried to treat the 'thin wire' as a template. This meant he began to lay down a set of thin wires in a line from the battery to the resistor.

Students C and H tried to wire 'through an object'. Student F, after choosing the command wire, tried to move directly from one object to another.



The Idea of Unwiring Student H quite plausibly decided that the command **unwire** applied to the named objects. That is, he wanted to unwire "res1" so he positioned the screen cursor on top of "res1". Student E seemed to think that the command **unwire** is active until all the wires to an object were detached. The implication is that the command **unwire** might be more sensibly renamed so that it reflects the idea of deleting a connection rather than freeing an object from any connections.

Independent Work Worksheets can provide useful guidance for students but there is always the possibility that they might impose too rigid a regime upon the student. In the observational period, student A followed the worksheets in a very haphazard way. He explored the system on his own. Students B and C waited until they had finished doing what was required before doing any exploration. The rest carefully followed the worksheets.

The Construction Phase

The eight students were now required to work their way through a set of ten worksheets. Each worksheet is designed to help the student answer one of the problems found in the misconception test.

Initially, it was planned to keep the worksheets very brief —mostly to remind the students of the problem and give them guidance about the system. The worksheets were then revised on the assumption that the students needed more guidance —which turned out to be the case. This extra guidance mainly took the form of an incomplete plan for the problem.

As one might expect most students were able to improve on the results of their test —see table 5-9. There were very few cases in which a student performed at a worse level for some problem. The simple explanation might be that, given a means of testing whether a potential option is right, they can correct their former beliefs in terms of the results of modelling the various problems. Some of the evidence, however, implies that even if students can model a problem they do not necessarily see that the data contradicts their beliefs.

	Student Identifier								
Question Number	A	B	C	D	E	F	G	H	Number Correct
1	c	-	c	c/d	all	c	all	c	4.5
2	a	-	a	a	a	a	-	a	6
3	c	-	c	-	c	c	e	c	5
4	c	d	d	b	d	d	b	d	5
5	d	d	d	b	d	d	a	-	5
6	d	a	a	a	d	a	c	a	5
7	d	a/d	c	c	b	d	d	d	2
8	b	b/d	b/d	-	c	b/d	b	b/d	4
9	d	d	d	d	d	d	d	-	7
10	d	d	d	d	d	c	d	d	7
Number Correct	7	5.5	9.5	5.5	6	7.5	3	6.5	50.5

1. Correct choices are emboldened
2. A correct choice given with another incorrect choice counts 0.5
3. Missing entries indicate that no decision was made about original
4. The entry "all" indicates that it was thought that all the possible options were true

Table 5-9: Circuit Construction Results

Rather than discuss each question separately the discussion that follows is in terms of a number of interesting issues.

Problems with Using ELAB A number of problems were identified that relate to the facilities provided by ELAB and some of the conventions that are required.

Wiring Up Objects There was only one occurrence of using the object 'thin wire' instead of the activity of wiring up. The conclusion is that the students learned to make the correct distinction quite quickly.

The requirement for wiring up to begin and end on either an object or a connecting wire caused some minor problems. Student B, for example, tried to model question two quite literally. As no facility was provided for students to create instances of the object class *node* his attempts were in vain.

There was also a continuation of the tendency first observed during the introductory phase in which students would expect to be able to 'wire through' an object. This afflicted most of the students at one time or another although there were relatively few occurrences.

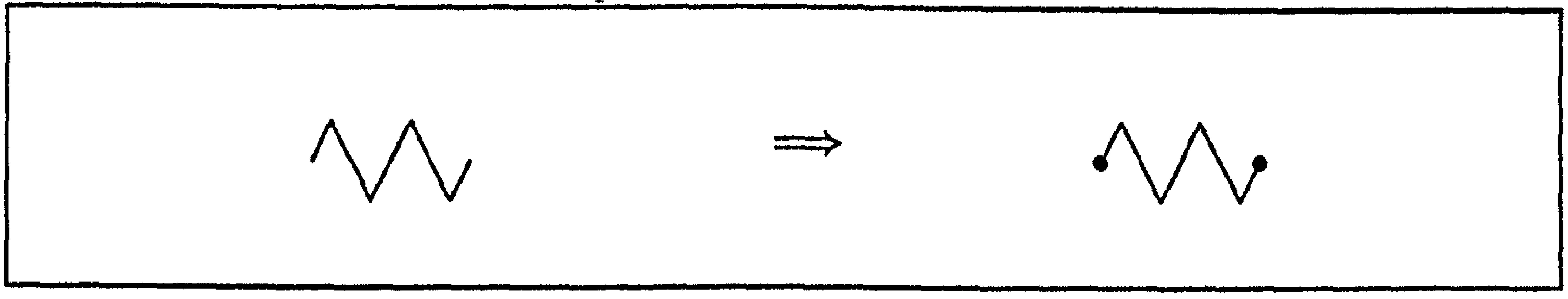
Unwiring Objects Only one instance occurred of a student trying to unwire an object by 'pointing' at the object instead of a single connection. Again, students learned the correct semantics with few problems.

There was some difficulty with the idea of moving only unconnected objects. This lead to some extra unnecessary effort which suggests that ELAB needs redesigning to allow students to take connected objects out of a circuit, move them about and place them back in the circuit. Yet this leads to problems about how the modified circuit is to be interpreted. If we stick to the preferred parallel with the real world then the command **move** should be **disconnect and move**.

A similar problem proved to hold for the **kill** command. The suggested remedy is to provide a **disconnect and kill** command.

Object Representation By far the worst problem for the students was the requirement that each object should have two ports. Each object was built to include two specific locations for the terminals. Yet frequently students would seek to wire up to the object without reference to these terminals.

The icons used by ELAB follow common physics textbook practice. This means that students are generally supposed to infer from the shape of an icon exactly where the terminals are. The implication is that students do not have a working knowledge of how to draw circuit diagrams of their own using this implicit information. The problem might well be alleviated if the location of these terminals were to be emphasised as below:



Problems with Students' Methodology The students were required to answer the same questions as they has already answered during the misconception test. The difference is that they could set up the situations described in the test and then make suitable changes. An analysis of their activity suggests a number of ways in which the students performed badly or, at the very least, sub-optimally.

Lack of Realism Student G, for example, had great difficulty imagining what a thin wire might be. He was able to make the distinction between thin and thick but he maintained that a thin wire was 1cm thick. In the context of question two, this led to data which suggested that it made no difference what kind of wire he used —which entirely accounts for his inability to make a decision *on the basis of the data.* He was even encouraged to re-evaluate his choices for thin and thick and he did —he revised his thick wire from 4cm thick to 3cm. Even the default diameter provided for the *thin wire* object class gave him no ideas.

Too Much Realism Question ten makes reference to an ammeter. Several students thought that they should provide the ammeter with a small resistance. This was a correct decision in terms of realism but they failed to realise that the resistance of the ammeter would have little effect on the result of changing the circuit —in terms of the statements that had to be evaluated by the students. It is a point like this which makes the detection of student difficulties very hard for it is likely that the most able and the least able will, for different reasons, fail to set the ammeter's resistance.

Failure to Confirm the Effects of Changes In question five, student G needed to increase the resistance of a bulb. To do this, he increased the wattage which the bulb was designed to produce. He did not check that this actually decreases the resistance of the bulb —assuming it is Ohmic. This lead to a situation in which none of the possible options fitted the data. He eventually chose the same wrong option that he had done in the test.

Failure to Control Variables Properly Student G exhibited the failure to change one variable at a time, most noticeably in question one. In that question, it is necessary to note that both the iron and the toaster, modelled by choosing instances of the resistor object class, receive equal default values for their resistance. The resulting data does not permit a clear decision. On being given the hint that he should change just one of the resistors, he proceeded to change both to the same new value for the resistance.

A more fortunate incident involving the same student took place while he was trying to increase the resistance of a bulb in question six. He increased the wattage, making the same mistake as he had done in question five, but, this time, he checked the resulting resistance. Having decided that the resistance had fallen, he increased the voltage at which the bulb was intended to operate. He again checked the resistance of the bulb and found that it had increased. Other students, when faced with the same problem, tended to reset the wattage and increase the operating voltage. It is reasonable to assume that student G has not developed the useful idea of holding all but one independent variable fixed.

Failure to Interpret Data Correctly It is not easy to disconnect the students' experimental abilities from their beliefs about physical phenomena. In many cases, it is possible to see a certain (unorthodox) logic at work.

Student C, who had obtained the correct answer for question one in the test, used data for question one which could not be interpreted as ruling out all but one of the options. He was so confident of the correct answer he did not bother to confirm that the other possibilities proffered were incorrect.

Perhaps question seven was the most interesting. The worksheet used did not ask the students to record the crucial measurement of the current actually flowing through the initial battery. Although it was certainly the case that this data was visible for all to see, four students failed to make the correct deduction. Interestingly enough, all eight students gave a different answer to this question than the one they gave in the test.

Student F, in question ten, failed to notice that the current through the ammeter and battery had increased. He chose the same incorrect option that he had chosen in the test. This suggests that he was fixated on only the data which had to do with the two arms of the circuit in parallel.

Problems with Students' Beliefs These can be categorised as problems connected with circuits, relationships between quantities and fundamental concepts.

Trouble with the Circuit During the discussion of question one of the misconception test, it was suggested that some students might have believed that the iron and toaster were wired in series despite the clear statement that they were wired in parallel. Two students had opted for the two objects having the same current —student B and student E. In the construction phase, student B made two separate attempts to model the situation and both times he constructed a series circuit. Student E had other problems in connection with controlling the variables in his circuit.

Student A initially put the iron and toaster in series for question one. He, realising his error, decided not to rewire. He chose to represent one object by two resistors and proceeded to add two more resistors on a parallel arm. Such a move is difficult to follow but can be detected provided the onlooker is prepared to try mapping the student's circuit onto the one required.

Trouble with Electrical Relationships Student G eventually chose the wrong option for question four on the basis that the brightness was related to the difference between the designed wattage and the electrical power loss.

The same student, in question one, had difficulty deciding which basic electrical property might be related to a bulb's 'brightness'. A similar but more general state of confusion relates to which property is most directly connected to the heat produced by a device.

At least four students believed that increasing the resistance of a bulb could be achieved by increasing the operational wattage. This is a further example of the Ohms's law p-prim mentioned previously and was most apparent during the construction of the circuit featured in question five.

The idea of defining a bulb's performance in terms of the power output for a given applied potential difference is evidently a very difficult one for both the S4 and S5 students.

Trouble with Fundamental Concepts Question eight provided a difficult situation to model as ELAB was programmed to show the net electrical power delivered to the circuit by a battery. This led to problems for students in interpreting the result that the power loss is zero. Despite the existence of a current, student C stated that

> Nothing really happened —I infer from that that the battery would not get warm

This simply indicates that the students do not have a clear idea about the various energy transformations going on in a circuit. However, in their attempt to explain what was going on there was evidence of the 'energy-circuit' concept. For example, from student B:

The resistance was so great that the energy given off by the battery is lost from the circuit and no energy passes through the ammeter

The Project Phase

There were six simple project worksheets which focussed on DC circuits. They were designed to give little or no clues about the best circuit to use. Therefore, the project phase provided an opportunity to see how students handled problems with less guidance.

One: To construct a circuit that has a bulb in it such that the bulb outputs the same power as its stated wattage.

Two: To construct a circuit using a resistor such that the resistor outputs 1kW.

Three: To construct a circuit using two resistors such that the ratio of the currents through the resistors is two.

Four: To construct a circuit using pieces of thin wire such that the ratio of their resistances is four.

Five: To construct a circuit using a resistor such that the resistor outputs 0.1kW. Then to add another battery so that the power output of the resistor is still .1KW but the current drain on the original battery is halved.

Six: To construct a circuit that has a bulb and two batteries in it such that if one of the batteries dies then there will be no change in the brightness of the bulb. The bulb is to output the same power as its stated wattage.

As might be imagined, there is further evidence of students finding the same sorts of problems with the modelling system as in their previous work. Yet their problems have diminished considerably.

Trouble with the Circuit Question three requires that students realise that placing the resistors in series is guaranteed not to work. Students A, D and E all started with the resistors in series. Each of them, however, rapidly set the resistances of the resistors in the correct ratio. They placed the resistors in parallel only after they realised that their expectations were wrong.

Question four did not require the two wires to be in series or in parallel but all chose to put them in parallel, with student E changing from a series to a parallel configuration.

Both question five and six required the two batteries to be placed in parallel. It was expected that there would be a tendency to place them in series. This turned out to be the case for question five but not for question six since, by that time, they had learned their lesson.

Students A and H evaded the problem in question five by replacing the original battery with two identical batteries with half the electromotive force. Student G placed the second battery in series and solved the problem by putting its electromotive force equal to zero. Of the other six students, only student F chose to wire the second battery in parallel with the other one straight away. Student E placed the second battery in series and realised his error before going any further. Students B, C and D only realised their error after running the analyser. Student D made the same mistake in question six.

Trouble with Electrical Relationships Both questions one and six require the students to realise that a bulb will produce its designed wattage when it is provided with a certain potential difference. Student A made no effort to solve this problem while student B tried and failed. Student G failed in question one but eventually succeeded in question six.

Perhaps question four illustrated the most interesting problem: that of the inverse relationship between the diameter of a uniform piece of wire and its resistance. In both the test and the construction phase only two students had any trouble with the qualitative concept that increased thickness means decreased resistance.

In this question it becomes apparent that the students are generally wedded to the idea of a linear relation. Students B, C and H went for changing the length rather than the wire's thickness. Student G, after an almost random attempt based on changing both the length and diameter of one wire, made both the length and thickness of one wire four times greater than the other one. This produced the required ratio! All the other four students placed the diameters in the ratio 1:4 at first. Student E quickly found the answer but the other three had to try several settings. Their strategy was mainly to change one wire's diameter at a time.

In both questions two and five the students need to make a resistor deliver a certain amount of power. This caused several of the students considerable difficulty. Student E used the formula $P = V^2/R$ in question two and almost certainly in question five as well. Most used some sensible search strategy — obtaining too high a reading for the power and then adjusting a specific parameter until the result was achieved. Yet student F, for example, made three separate attempts to solve question two. He only succeeded once he had solved question five using the formula. Student A resorted to the formula for question five although he found the correct answer in question two quite quickly. Student A and C's performances, measured in terms of the number of times a parameter was set, deteriorated badly.

Discussion

First of all, some comments are required concerning the overall patterns of response. Some further details can be found in appendix M.

Performance Validity The test was designed on the basis of known problems with electrical concepts. Is there any evidence that those who did best were those with the least number of relevant problems? There is enough to suggest that further work might validate such a belief.

Two independent measures of overall physics ability were available: the results of both the 'O' and 'H' grade examinations. Three measures of performance were selected: the results from the misconception test, results from the construction phase and the improvement in performance observed. Spearman's rank correlation method was applied. To summarise, there was no significant correlation between any of the performance measures and 'O' grade success. There was significant (5% level) correlation for each of the performance measures with the 'H' grade results.

Although this evidence suggests an interesting relationship between performance and eventual school success at physics it is too fragile a connection to explore here. All the measures used fail to directly measure the number of misconceptions that the student possesses. Further work would be needed to extract the necessary information.

Performance Consistency It is noticeable that the improvement in performance between the misconception test results and the construction phase results was very high for some questions while it was low for others. For example, there was no improvement for questions one and two while the performance for question seven actually dropped a little. The greatest improvements were for questions three, nine and ten.

Using the analysis outlined in table 5–6 it is possible to make a crude test of the hypothesis that performance is correlated with question complexity. The improvement in performance was correlated against three different measures of complexity: the number of essential facts per question, the number of inferences required per question and the total number of facts and inferences. Spearman's rank correlation method was again applied. The results indicate strongest correlation (significant at 1% level) between the improvement in performance and the total number of facts and inferences. There was no correlation between the improvement in performance and the number of inferences.

In accounting for this it must be remembered that the data recorded in table 5–6 is by no means correct. It represents one of several possible analyses. The evidence suggests that students are faced with a real difficulty in handling complex questions without some assistance. ELAB certainly provides the student with some help —the question as to whether ELAB meets the further requirements needed to ensure that learning takes place must be settled elsewhere.

Summary A number of interesting beliefs surfaced about the various properties and electrical relationships. Generally, these were inferred from the available evidence.

Further to this, more evidence surfaced about the inability of able students. Even students who are fifteen years of age were not capable of applying certain methods of scientific investigation. A common observation would be to assert that the students who failed to exhibit the more sophisticated scientific behaviour had not reached the Piagetian stage of formal operations. This may be the case but there is at least one other relevant factor: many students doing practical work are provided with an experiment in which only one variable is manipulated.

Further, the educational map of physics is organised so that students encounter simple situations before complex ones. Unfortunately, there are certain conceptual hurdles that cannot be handled as a series of small incremental steps. Either the student can evade some of the key steps in experimental method with the connivance of the system or s/he must be put in situations where the mastery of such methods is necessary. The inconclusive but significant indication from the experiments with ELAB is that even able students in their last year at school are not placed frequently enough in open ended situations where certain desirable methods are essential if they are to succeed with some project.

5.7 Some Conclusions

A system such as ELAB poses a problem. It would be plausible to argue that the provision of such a system does not free the student at all. It may simply replace some given task with other (tedious) tasks. Worse, these new tasks might be even more difficult to perform than the old ones that have been replaced. For example, the student has to learn how to cope with the abstract representation of the circuit used by ELAB rather than a concrete circuit. As a consequence, there are a number of difficulties in constructing and altering the representation of the circuit that may not exist in relation to 'real' circuits.

It is believed that there are good reasons why this position is not correct. Not only does the use of ELAB expose some inadequacies in the students' understanding of electrical properties and processes but it has become increasingly apparent that there are inadequacies in the training that the students receive.

5.7.1 ELAB and some Educational Issues

Inevitably, much of what has already been said in section 4.6.1 applies here also. Rather than go over exactly the same ground the intention is to point out any issues that are specific to ELAB.

5.7.2 ELAB as a Modelling Environment

Extensible Object Classes

The main issues that need attention include providing an extensible user interface which would permit the students' own circuits to be integrated into the set of object classes available through the Class Window.

The important part of this idea, however, is that the system should permit the student to define incomplete circuits which can become new functional units. The programming analogy has been outlined in section 5.5.4.

This would allow both the top-down and bottom-up development of quite complex circuits —particularly if certain non-linear devices were added to the set of basic electrical classes. For example, this would permit the definition of a simple ammeter class which would allow teachers the opportunity of providing such a class with the later opportunity of discussing the basic principles.

Implications for the User Interface

An acceptable implication for the user-interface would be the provision of scroll up/scroll down menus in various system windows. Circuits also lend themselves reasonably well to the automatic generation of icons which can stand for some class of circuit.

The Analyser

The basic problem with the current circuit analyser is the same problem that existed for SOPHIE I [Brown et al 75]. The first version of SOPHIE, a sophisticated aid to help students learn to troubleshoot a defective circuit, made use of SPICE [Nagel & Pederson 73]. This is another sophisticated program but it uses methods of circuit analysis that are far from those which human experts use. Therefore it proved difficult to generate appropriate explanations of how the analysis was going and why various choices were made.

It has already been pointed out that the analyser used by ELAB is a simple loop analyser. Current loops are detected, equations are constructed using Kirchhoff's laws and then solved using a matrix method.

This deliberately implements a method that is potentially accessible to students. Unfortunately, the students in S4 and S5 do not necessarily learn this method. In England, students that might be able to handle the method would normally be in their 'A' level year. There are two more important things that the student might learn with the help of a suitable analyser: a methodology for circuit analysis and a better understanding of how circuits behave.

The Methodology of Circuit Analysis What the students need to learn is closer to a collection of methods. These relate to how to select and apply some simple rules and principles for circuit analysis.

Such a collection of methods may not be sufficient to solve all the circuits that the current analyser can handle. Nevertheless, it reflects a level of understanding which is desirable and which can form the basis for the development of a deeper understanding which can cope with more complex circuits.

A Trace Package Providing the student with an explanation of what happens in the circuit on the basis of, for example, current flow could help students to build their own models as to what may be happening inside a circuit. Alternatively, it may well expose various inadequacies in some particular model. This issue is expanded on in the next chapter.

5.7.3 ELAB and Misconceptions

A number of misconceptions relating to the understanding of electrical circuit have been mentioned in this chapter. These are now collected and briefly discussed.

Wants-X—Gets-X

At one level of abstraction, circuits can be seen as the means by which certain 'substances' are transmitted. Objects are seen as agents which determine whether transmission is to be encouraged or hindered. Some objects are recognised as active agents which may initiate a transmission by 'pulling' or 'pushing' while other objects are passive in that they only react to the consequences of the active agents' influences.

It is quite plausible therefore that students may envisage a number of different substances being transmitted around the circuit —possibly, along different paths. Therefore, there are a number of misconceptions that are related to the idea of certain objects initiating demands for some state of affairs to hold.

The *wants-X—gets-X* misconception might be defined as the belief that

> If an object wants X units of property Y then it gets X units of property Y[15]

This version of the misconception seems to discount the possibility that X units are unavailable. Anyone holding this misconception has no need to further justify what transactions are needed in order to obtain the required quantity. They may not appreciate whether any conservation laws apply.

Examples include:

- wants-current—gets-current
- wants-power—gets-power
- wants-PD—gets-PD

All the instantiations of "X" require that a quantity of the property can be part of some transaction. Experience therefore suggests that it would be rare to find students with a misconception *wants-resistance–gets-resistance* as little discourse is focussed around any such idea as 'flow of resistance' and the resistance is the property of an object with a constant value.

There is another version which is

> If an object wants X units of property Y and at least X units are available then it gets X units of property Y

The possessor of this version might well believe that some conservation rule is applicable. The use of the word "available" is intended to obscure the exact means by which quantities of some property are transmitted.

A further variant is the misconception *largest-need-for-Y—gets-most-of-Y* which is:

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[15]The idea of 'wanting X units of property Y' is more correctly written as "the value of property Y is to be increased by X units".

> If $object_i$ requests X_i units of some quantity and if Y units of the quantity are available then $object_i$ gets $\frac{X_i}{\Sigma X_i}.Y$ units

Again, the exact amount 'available' needs further examination.

The above has avoided discussion about the nature of the substance(s) transmitted and whether or not the transmission is continuous or discrete.

Ohm's Law P-Prim

This can be paraphrased as:

> The larger the quantity of property Y the larger the quantity of property Z where Y and Z are connected in some way

Examples are:

- more-material—more-resistance
- more-wattage—more-resistance
- more-resistance—more-power
- more-batteries—more-PD

There is a tendency for students to believe that such laws are linear. Any non-linear situation which conforms to the Ohm's law p-prim can prove difficult for students to handle.

Misconceptions about Objects

Certain misconceptions may be categorised as being object-specific. For example, the *battery-supplies-constant-current* misconception or the *more-batteries-in-parallel—less-PD* misconception.

A further misconception was identified in relation to bulbs: the belief that the brightness of a bulb is proportional to the *designed* wattage minus the actual power lost when the bulb is in circuit. This suggests that a student holding such a belief sees the energy converted from the electrical form into light as being subject to a leakage which is the actual power loss measured. This may be due to the student having induced a belief that all power loss is conversion of electrical energy into heat energy. Applying this idea to a typical resistor leads to the explanation as to why the resistor does not shine —that the 'leakage' of electrical energy into heat leaves nothing over for conversion to light.

Misconceptions and Primary Focus

The idea of the *primary focus* has already been introduced. The misconception of interest is the belief that no changes take place to the quantities input to —or output from— the 'primary focus'. This belief was named the *no-changes-outside-primary-focus.*

Circuit Misconceptions

There are a number of possible misconceptions that relate to the circuit level of description.

These include the *circuit-overlay* misconception described earlier and the *circuit-matching* misconception which relates to the criteria used by students to determine when two circuits are equivalent.

Misconceptions about Electrical Properties

Several misconceptions relate strongly to beliefs about current, potential difference etc.

Current For example, the *clashing-currents* model in which there is both a current from the positive terminal and a current from the negative terminal. This was not observed during the study described previously.

Another misconception relates to the *current-consumption* model in which current is consumed as it goes round the circuit. This misconception was detected and seems to be related in some way to the abstract concept of quantities flowing round circuits.

There is at least one more misconception based on current being shared equally between objects —but not conserved.

Resistance Apart from any misconceptions relating to resistance and mentioned above, there is the *no-resistance—no-current* misconception.

Potential Difference The *adding-objects-in-parallel-does-not-effect-the-PD* misconception. This does not seem as general purpose as the *no-changes-outside-primary-focus* misconception but it might boil down to the same thing.

Power Flow There is a strong suggestion that students envisage a power circuit analogous to the current circuit. Students naturally believe that objects use up the power as it flows through. If the student envisages both a current circuit and a power circuit then it would be quite understandable if they were to conflate the two flows on occasions.

The above concept of a power circuit is not a misconception but it may help to explain how the current flow misconception arises in which the current is 'used up'. Other possible misconceptions include ones relating to the behaviour of objects in series.

> If there are n objects connected in series and if $object_i$ wants P_i units of power then the amount of power that 'flows' is $min(P_i)$ units
>
> If there are n objects connected in series and if $object_i$ wants P_i units of power then the amount of power that 'flows' is $max(P_i)$ units

In the first of the above beliefs, an object is seen as a kind of gate, or hindrance. In the second case, the objects are seen as power flow facilitators.

5.8 Summary

This chapter has featured an analysis of the problems that students have in learning about electricity with special reference to simple electrical circuits. As in the dynamics case, recent research results indicate that students often possess misconceptions about electricity.

Again, the methodology used involved giving students a misconception test followed by opportunities to model the situations that featured in the test. The eight students proved both able to use the system and to learn from the confrontations that arose. The initial results obtained support this use of ELAB.

Again, the results from both the test and the use of the modelling environment provide further evidence as to the nature and ubiquity of a number of misconceptions about electricity. Some observations follow:

- Students hold misconceptions about the topology of electrical circuits and the structure of objects found in electrical circuits.

- On the assumption of rational behaviour by the students, it would appear that previous accounts (e.g. [Cohen et al 83, Shipstone 84]) of students' misconceptions are not sufficiently detailed.

- There is some evidence for the existence of 'mal-rules'. For example, that "adding a resistor in parallel has no effect (on currents or potentials)".

- There are indications that misconceptions can be compounded.

- Again, student have problems with controlling variables. Even if students were able to identify that a functional relationship held between a number of variables they were often weak at handling non-linear (direct or inverse) relationships.

ELAB facilitated confrontations between the students' beliefs and their observations. However, the misconceptions that relate to the way in which electrical changes occur were not explored. The next chapter includes an outline of what is needed to improve the ELAB environment based on the results derived from the last two chapters.

Chapter 6

Conclusion

It is maintained that there are strong reasons why the modelling approach to learning outlined in earlier chapters should be pursued further. Here, the specific strengths and weaknesses of both DYNLAB and ELAB are discussed in relation to wider issues.

In particular, this chapter is divided up into sections that deal with to the specific issues directly relevant to DYNLAB and ELAB, ways in which the work might be extended and the current educational context.

Finally, the contributions of this thesis are briefly summarised.

6.1 Some Specific Results

The contributions of the thesis are now outlined in relation to the work undertaken in connection with the design and use of DYNLAB[1] and ELAB.

[1]The discussion of the work based on DYNLAB incorporates work also done on ROCKET.

6.1.1 Modelling is Practical

In short, experience in using both DYNLAB and ELAB suggests that it is practical to require students to build and run models. Despite some weaknesses in the user interfaces, both systems proved reasonably easy for students to manage.

A number of design issues were seen to be important:

- The separation of model building from model execution: the system *may* be working hard behind the scenes in preliminary evaluation of the partly built model but the student should see a clear distinction between these phases. There is a strong commitment here to the belief that immediate feedback about the 'quality' of the model is a poor aid in the construction of clear conceptual models[2]. The argument that delaying criticism of the model will encourage misconceptions is regarded as insignificant in the light of the evidence that misconceptions are extraordinarily deeply rooted.

- The importance of a good graphical interface and the concept of the graphical representation of the model being constructed. The representation should be regarded as an aspect of the student's working memory and to be respected as such. The implication is that as few unrequested alterations as possible should be made to the screen by the system.

- Defaults are required to permit quick model construction. It might be found desirable to allow the model components to be parameterised but simple default components should be provided.

- Tampering with model interpreters is regarded as placing too great a load on students. This principle, however, does not exclude the possibility of making the domain dependent principles completely explicit and modifiable.

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[2]This does not rule out the possibility of providing passive critics which the user might learn to use to get advice about the properties of the model.

There are, however, a number of practical issues that have been identified as requiring some attention:

- The standard practice of providing each kind of model component with a number of properties has consequent problems for naive physicists. Some properties —such as mass— are seen as being part of the definition of a component and immutable. Other properties —such as velocity— are seen as contingent and mutable. This distinction depends on context but it may prove advantageous to respect it.

- The reification of abstract entities is always a possibility with modelling systems. That is, the properties defined in the model are phenomenological entities. For example, that the energy stored in a battery *really* flows round an electrical circuit. More work is needed to map out the associated problems.

- A simple and reliable metaphor is needed for the modelling activity. The object-oriented metaphor used with both DYNLAB and ELAB was found to be useful. Yet, in section 4.6.3, it is also stated that an object-oriented language which included concurrency might prove very useful. The issues relating to the provision of a concurrent object-oriented metaphor have been touched on by Gould and Finzer [Gould & Finzer 84] and Chung has investigated the use of such a language [Chung 86]. Further exploration is needed in connection with how well students can actually manage such modelling environments.

6.1.2 Modelling Needs Extra Support

On occasions, students were observed to struggle with the modelling activity. It is therefore worth considering the nature of the tools that might be useful to the student. The assumption is made that such tools would not, in general, inform the the student unless explicitly invoked —even if these tools were to be continuously active. This is to preserve the tool-based approach considered throughout the thesis. In a context in which there is a more direct tutorial component then modelling aids could take a more active rôle.

These tools include:

- A 'help' package. The student would be able to browse freely through the information available. In general, providing easy access to the desired information is a difficult problem.

- Powerful explanation generators. These depend on the existence of a number of model interpreters which are able to provide alternative accounts. These may be variant accounts from substantially the same viewpoint or accounts from various perspectives.

- An experimental method checker. Such systems do exist and would continually monitor the student's activities. Rowell provides a theoretical analysis of strategies connected with the control of variables which would need to be taken into account [Rowell 84].

6.1.3 Handling Misconceptions

A large number of misconceptions reported in the literature were re-examined and their widespread occurrence further confirmed. The use of both DYNLAB and ELAB proved to have a number of specific benefits in detecting certain classes of problems. The following is a summary organised around various aspects of the usage of these systems. First, some specific uses that proved beneficial. This is followed by four aspects: the underlying physics, the modelling phase, experimental methodology and interpretation of data. The divisions are not hard and fast in that, for example, a problem relating to the correct interpretation of data may depend crucially on some problem with the underlying physics.

Some Specific Uses

ELAB and DYNLAB were both useful in fairly predictable ways. Experiments could be set up by the students, measurements requested and hypotheses supported or falsified. Nevertheless there were a number of other uses that might be listed:

- The exploration of how to change the direction of a body in motion using impulses. DYNLAB seemed to be more effective than ROCKET in helping students to formulate their ideas.

- The implications of Newton's second law of motion were explored in both static and dynamic situations. A number of misconceptions were detectable.

- The explicit modelling of non-Newtonian notions was detectable.

- Problems with the distinction between force and impulses were observed.

- ELAB provided the opportunity for students to practice the construction of circuits —much needed, as it turned out.

- Problems connected with the physics of bulbs and notions about resistance were explored.

Some uses were not explored. For example, it would have been possible to fault a model and ask the student to fix the situation given a description of the required behaviour. Another usage of ELAB which was not explored was the way in which both Kirchhoff's current law and his voltage law could be induced from using the circuit analyser.

Problems with the Underlying Physics

Some of the kinds of problems that students had with their understanding of basic physics concepts are listed:

- It proved possible to detect reasoning involving untyped influences in conversations with students. For example, adding an impulse of ten units to a velocity of ten units to bring a body to rest.

- Problems relating to which electrical property corresponds best to the heat output of a device were detected using ELAB.

- Problems relating to the specification of a bulb's performance were detected using ELAB.

- Confusion between the idea of electrical and other forms of energy was detected using ELAB.

Problems with Model Building

Some problems with the actual process of model building were found:

- Confusion between the name and position of an object —this can only show up in an environment where some of the components move.

- Problem simplification through changing or underspecifying the geometry of the model.

- Failure of some students to concern themselves with the initial conditions of a situation.

- Lack of realism leading to models that cannot exhibit the required behaviour.

- Modelling that is unnecessarily faithful to reality.

Problems with Experimental Methodology

Students often did not possess the necessary skills to efficiently solve problems. Their methodological problems included:

- Failure to check that the desired effect of a change had occurred.

- Failure to control variables properly.

Problems with Interpreting Evidence

These problems are, on the whole, very general ones:

- It proved possible to detect that some students remembered real behaviour incorrectly.

- Many students did not manage to handle signed quantities while using ELAB. Current, potential difference and power conversion are all subject to such difficulties.

- Failure to match objects in ELAB with idealised objects in physics lessons. This suggests a failure to understand the notation used by teachers and text books to describe circuits.

- Failure to make correct judgements from data. Quite frequently, students would not notice that a given result actually contradicted the explicit hypothesis that they were entertaining.

6.1.4 The Contribution of the Methodology

It is worth commenting on the methodology described initially in section 2.7.1 and used with both DYNLAB and ELAB. That is, the methodology of using a *Misconception Test* together with modelling work on the situations described in the test.

First, some important points about the nature of *Misconception Tests*:

- They are designed in close conjunction with the modelling systems. The design of both the test and the modelling environment are intimately connected.

- These 'tests' provide opportunities to extract as much information as possible about the beliefs of the students. They are not designed to discriminate between expert and inexpert students or to provide some idea of the mastery of a topic.

- They are designed to focus on situations that are known to be associated with at least one potential misconception. Hence they should be validated in terms of how well they *confront* students' range of conceptions about some situation.

- A well designed test should encourage the students to be explicit about their comprehension of the problem and their beliefs about the situation.

The results of such a test provide a control on the progress of the students through the modelling phase. This modelling phase is designed to take the student through a construction of each of the situations found in the *Misconception Test*. In constructing each situation the students may echo the beliefs that surfaced in the test. It is also possible to observe the emergence of other misconceptions which had not previously appeared. The aim is to force the student to reflect on the processes at work through the activity of modelling.

It is believed that this methodology is novel and that it can be exploited in a range of domains. It also offers an interesting approach to the use of computers in the classroom.

6.1.5 The Place of Modelling in Education

Modelling environments specialised for specific domains can be used in a way that fits in with the current physics curricula. There are, however, a number of advantages in the use of such environments that do not fit in well at all: the exploration of inadequate or 'incorrect' models and the transition from one model to a new one. The problem lies in recognising a curriculum need —that a less than ideal model is still a subject for explicit, possibly qualitative, exploration.

The curriculum implications of the thesis are summarised first in relation to specific implications for dynamics and electrical circuits. A list of the wider implications follows.

Issues relating to dynamics:

- Two dimensional vector experience should come before the so-called one dimensional vector treatment.
- Dynamics experience should come before kinematics.
- Experience with impulses forms a natural introduction to forces.
- Earliest possible introduction to frictionless systems.

Issues relating to electrical circuits:

- Practice should be given in the construction of circuit diagrams.
- More attention needs to be given to the problems relating to the specification of a bulb's performance.
- Practical experience with the conversion of energy from one form to another is needed.

The wider issues:

- Redundant physics principles may be a way of saving time in the coverage of the curriculum material but do not promote a robust understanding of principles. A good example is the rule for obtaining no current in the Wheatstone bridge problem illustrated in figure 5–2.
- The exploration of 'bad' models needs a place in the curriculum. The curriculum process might, however, tend to 'freeze' the description of what inadequate, or incorrect, models should be explored. The provision of a modelling environment gives greater scope for flexible curriculum development.

- The design of misconception 'tests' and practical work based on them is feasible and needs further exploration to assess the effectiveness and suitability for building such work into the standard curriculum.

In the classroom, modelling environments can be used successfully in traditional ways: setting up demonstrations, testing students' experimental methodology and so on. On the other hand, modelling environments have several other functions.

- Enabling the exploration of the implications of incomplete or incorrect models
- Aiding the construction and performance of critical experiments
- Exposing underlying misconceptions
- Allowing for the construction of new models from old

Each of these aspects requires the teacher to possess special skills. In order, for example, to encourage the exploration of a given model the teacher will need to be aware of the class(es) of models that can be constructed. Sometimes the teacher will not know the implications of a model built by the student. Sometimes the student might know more about the current model than the teacher. This means that the teacher may have to adopt an unaccustomed rôle —s/he must be prepared to help the student design a research program to explore the model. To do this, the teacher must be willing to accept the student's model for what it is and think carefully about whether, or when, woeful inadequacies should be pointed out.

The student is confronted with a requirement to learn a complex system. To save time, the user interface needs to be uniform across a number of specialised modelling environments. The underlying vocabulary of modelling any system has to be learned. The student needs to participate in modelling all aspects of the situation —both the structure and the behaviour of models. In order for this to work, students are needed who are mature enough to handle the concept of alternative physical theories. Although no attention has been given to investigating whether students are capable of accepting that there may be several competing theories it is believed that many students in S4 and S5 are capable of so doing.

6.2 Describing Circuit Behaviour

The previous work on the problems that students have with electrical circuits indicated that many, if not all, students have problems in building a clear conceptual model of how and why current 'flows' in a circuit. The basic approach taken throughout this thesis is that, as far as is possible, students must engage in explicit modelling —in this case, of circuit behaviour. DYNLAB provided a simple environment to explore particle behaviour but the first version of ELAB did not address the corresponding issue in the electrical domain. It is therefore necessary to consider how this problem can be addressed.

The discussion is broken into three parts: the fundamental problem is outlined in greater detail, possible approaches are outlined and, finally, a promising line of research and development is indicated.

6.2.1 The Problem

Many misconceptions about electrical circuits are related to the beliefs held about the behaviour of electricity. For example, if two identical bulbs are to be arranged to burn equally brightly then it is sensible, but not essential, to put them in series.

A student who holds the unipolar model of electrical current might not do this. Such a student might not place the bulbs in series because a possible implication is that one of the bulbs will not light at all. Trying to deduce this possible misconception from data derived only from observations of the circuit under construction would be extremely difficult. The record of the student's attempt to model current behaviour explicitly is likely to be of more use.

Note that it cannot be assumed that, once students who possessed the unipolar model have learned how to light a bulb using wire and a battery, they no longer hold this misconception. This is far too optimistic a view. The student *may* generate a new model but may also patch up the old one by regarding the complete circuit requirement as somehow distinct from the problem of how electricity flows. The point here is that students may spend quite some time learning the syntax of circuits without strongly undermining their beliefs about the nature of electrical behaviour.

Given that it would be desirable for ELAB to provide the facility to model circuit behaviour, there is a serious, but predictable, difficulty: can the modelling interface be designed so that most of the complexities are handled by the system leaving the student free to concentrate on how to combine a small number of underlying primitive ideas? It is possible to state some of the requirements that any solution to the problem of modelling circuit behaviour should satisfy:

- There should be a small number of primitives.
- These primitives should be conceptually close to concepts that students already use. These terms will then have some interpretation even though this may be, in some sense, wrong. This is an approach diametrically opposite to providing new ones with no obvious connotations.
- There should be very few mathematical relationships needed. Most of the modelling should be at a 'qualitative' level with the system selecting appropriate equations when it proves necessary to do so.
- The models that can be built should be easy to construct and easy to change.
- The well-known faulty models of electrical behaviour must be constructible.
- A fairly standard 'correct' model of behaviour must be constructible.

- The class of models produced should be handled by a single interpreter. Each model should produce, when interpreted, 'sensible' behaviour.

The next step is to outline the nature of a possible solution to the problem.

6.2.2 Possible Solutions

One of the natural starting points is the system dynamics approach. It is argued that the advantages of providing a firm theoretical framework for extending ELAB are more than outweighed by the extra work needed to install a variety of environmental features. The better facilities offered by various object-oriented environments provide strong advantages.

System Dynamics

This approach provides the theoretical basis for the modelling of a class of systems in terms of the *flow* of some quantity between *compartments* —the flows being regulated by *valves* and the *state* of the model being defined by the contents of the compartments —the *state variables.*

An example of a system that uses this formalism is STELLA —a Structural Thinking, Experiential Learning Laboratory with Animation [Lewis 86, Jones 86]. The builders of ECO —an intelligent front end to an ecological modelling system— also used this formalism in an attempt to help ecologists to build simulation models [Uschold et al 84]. Criticisms of this approach has led them to change their approach [Uschold et al 84, Muetzelfeldt et al 86]. A brief discussion of the problems follows.

Too Powerful The constraints that are placed on the valves can be differential equations, difference equations etc. where the variable quantities are the state variables. The formalism therefore places few constraints on the way in which flows are controlled. Some restriction on the types of allowable constraints is desirable —if only to relieve the modelling burden on the student.

A similar criticism can be made about the nature of the compartments. Often, different layers of abstraction have to be collapsed to create the required single network.

Too Abstract The formalism is capable of describing a number of superficially dissimilar systems. It would be reasonable to expect a trade-off between the generality that permits the application of the formalism and the ease of expression. That is, the more distinct situations to which the description language applies the harder the language is to use. Here, "harder" implies some measure of the distance between the natural descriptions generated by students and the system dynamics description.

Not Powerful Enough There is no way to capture the distinction made by novices between a compartment wanting to push stuff out or wanting to pull stuff into it. This distinction collapses into a unidirectional flow of 'stuff' in system dynamics. Assigning intentionality to objects is done by both novices and experts. It is assumed here that such an assignment by novices is a significant and necessary step on the way to a more abstract consideration of systems. The expert may use the same language but is usually able to contemplate different possible explanations depending on the context.

Another distinction that is needed is between a flow of stuff of different types. For example, a naive student may conceive of a particulate model of electrical current involving a flow of electrons. Various compartments consume electrons and the number of electrons returning to the source is reduced. This model is equivalent to one of the models of current described by Osborne [Osborne 81]. A more sophisticated model might require that there is a flow of electrons but that the compartments modify values of properties of the electrons.

The Object Oriented Approach

In section 1.3, we considered Smalltalk as providing an interesting modelling environment. The building of modelling environments on top of Smalltalk has shown that it possible to develop interesting experimental frameworks. Examples include THINGLAB, discussed briefly in section 1.3.2, the Rehearsal World [Gould & Finzer 84] and the Alternate Reality Kit [Smith 86]. The Rehearsal World is an exploration of the metaphor of programming by rehearsing a troupe of actors while the Alternate Reality Kit (ARK) provides a reasonably clean distinction between an alternative reality and the so-called *meta reality* in which events occur that are not part of the alternative reality. All these environments are able to access the programming power of the underlying Smalltalk language.

These examples illustrate the potential of the Smalltalk environment to form the basis for providing the desired properties described in section 6.2.1 and the extensions described later in section 6.3.

6.2.3 The Prognosis

The development of a suitable circuit behaviour modelling component for ELAB is believed to be feasible. The description language can be designed so that it compiles to an internal formalism close to that of system dynamics but much work would be needed to add the user interface to compensate for the inadequacies of the approach. Smalltalk-80 (and its kin) offers desirable environmental features and provide the power to implement the necessary interpreter that can handle the required class of models. The various design requirements mentioned in section 6.2.1 can be satisfied.

6.3 Further Work

This section is devoted to developments that can be begun immediately while section 6.4 addresses the possible contribution of other research. Section 6.2 also features a description of work which is complementary to that discussed in this section.

An outline of a new design for a modelling system is given which allows beliefs about both dynamics and electrical systems to be modelled in a straightforward way. The basis is a simple language which lends itself well to both building theories and to interpretation by computer. The work in building both DYNLAB and ELAB is therefore generalised and extended.

For simplicity, the basic structure of ELAB is assumed and areas for change and improvement are outlined.

6.3.1 Model Structure

Modelling objects, initial conditions and constraints are considered here.

Modelling Objects

The extensions needed to make ELAB a more useful environment are described. These cover issues related to object classes, the set of permissible properties and the set of permissible relations.

Adding Arbitrary Object Classes The student should be able to specialise and occasionally generalise definitions of object classes. For an example of specialising, the student could create an instance of resistor that always had a resistance of ten ohms and create the object class *MyResistor*. A generalisation would be to create the class *Real Battery* which had the properties of emf and resistance.

It is obvious that the above cannot be realised unless inheritance is built into the scheme for specialising and allows arbitrary addition of properties from the fixed set of properties in use. Thus a real battery might be defined as an ideal battery with the extra property of resistance.

This can be accomplished by providing one extra activity —equivalent to the definition of a procedure: the user constructs an object on the screen. It is assumed that, for it to be of use, the object has a pair of open terminals. Then the definition is given a name, iconised and saved. From now on, this icon will appear as a possible selection from the set of *Object Classes*. Thus the class *Real Battery* could be defined as a battery in series with a resistor. This would also allow specialisation in that a unit resistor is a two terminal open circuit with a single resistor which has been set to one ohm.

Adding Arbitrary Properties Currently, there is a finite and fixed set of properties used by ELAB. Is this list to be extended? Once arbitrary properties are permitted this will entail arbitrary relations[3] and provides some support for the move towards a system dynamics modelling approach. It would then be easier to extend the system to model water circuits and some dynamics concepts.

Is it really desirable to have batteries with the property of being red? Is there any advantage? If the student chooses to add an arbitrary property without defining how this property affects the behaviour of an object then it should come as no great surprise to the student that this property features nowhere in the trace/explanation of events. If, however, a limited number of primitives can be used to build new properties in well defined ways then it should be possible to build a suitable interpreter to handle the student's definition of the property. This approach fits the system design well.

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[3]Because there is no point in having a property unless it is related to some other property and/or the interpreter can handle the property in the scheme of things.

The main advantage in permitting extra properties lies in allowing the students to play with how circuits behave in terms of propagating changes. This aspect was absent from ELAB but is greatly needed.

Also, note that if extra properties can be added then the student should be allowed to delete properties too. One implication is that the analyser has to be robust enough to recover from properties and relations that are badly defined.

Adding Arbitrary Relations At the moment, the relations between properties in ELAB are predefined —for example, the resistance of a *Thin Wire* is predefined as proportional to length over cross sectional area.

Students can still *model their own mistaken beliefs* even with a fixed set of possible properties. If it is accepted that it should be possible to add arbitrary properties then it does not follow that there is also a need for arbitrary relations. Again, a building blocks approach suggests a small number of fundamental relations from which more complex relations can be built.

The definition of new relations from old and, for that matter, new properties from old ones can be accomplished through a graphical interface. An example of how this might be done in a very general way exists [Borning 85b].

The next question might be: how many of their mistaken beliefs can be modelled in this way? Certainly not all of them. If extra relationships are allowed then it will be necessary to distinguish between local relations and global ones. Also, an analyser has to be built to handle the extra rules.

Describing Initial Conditions

DYNLAB allowed the user to define a set of interesting events and a set of initialisations needed for the values of properties associated with the object. The distinction was blurred in that both sets of facts were kept in the same 'object'. This problem did not arise in ELAB as the facility to specify interesting events was not provided. Something more about the specification of events is found in section 6.3.2.

Describing Constraints

Constraints are recognised as a powerful way of describing systems. They have, for example, been used as the basis of circuit analysis by Sussman and Steele [Sussman & Steele 80]. Nevertheless, de Kleer has endeavoured to remove any constraints that operate on more than a single component [de Kleer 84]. He has pointed out the difficulty of removing Kirchhoff's Voltage law. If such formal constraints are needed then they must be represented in some way.

6.3.2 Model Behaviour

The specification of interesting events, the modelling of influences, the interpretation of the model and the provision of explanations are briefly considered.

Specifying Interesting Events

The ability to define exactly which events are noteworthy is a very useful facility. The detection of the occurrence or non-occurrence of something significant provides additional leverage on offering explanations as to how certain events occurred. Since the student has indicated an interest it can be supposed that *sometimes* the student might want to confirm an expectation or detect the occurrence of an unwanted event. Justification of how the event succeeded may be possible but offering an explanation for why some event did not occur is altogether more difficult. Of course, knowing why the event is interesting is even more useful.

Modelling Influences

An *influence* is a qualitative description of how the value of some object's property changes as the values of a number of properties change. An *influence equation* is a representation of such a description in equational form. Various aspects of individual behaviour can be represented by a fairly large set of such influence equations. A graphical interface can be provided so that each influence equation can be shown separately. Deriving a qualitative representation of an influence from a quantitative equation is reasonably straightforward but trying to generate plausible quantitative representations from a qualitative description is a much harder problem.

Interpreting the Model

Each influence equation can be used to derive an equation that will be used by the interpreter. Quantitative equations are needed for a quantitative analysis and qualitative equations for a standard qualitative analysis.

Explanations

It is desirable to offer explanations of various sorts at various levels. The addition of such facilities is not entirely a short term matter. For example, building certain sorts of quantitative explanation is reasonably straight forward. The provision of qualitative explanations is less easy. The question of providing *appropriate* analogical explanations is quite hard.

Quantitative Explanations This is orthogonal to the question of extending ELAB in terms of extra object classes, properties and so on. Is the method of analysis currently used redeemable in terms of offering an explanation? It would be easy to offer one which a limited number of students would understand —but not one that most students in S4 or S5 would accept. Many analysers would be needed. Each one should represent a way in which the students might analyse the circuit given what they know. They would combine symbolic analysis with, finally, a quantitative solution. This indicates that the program is fuelled with a number of principles which may be *in* or *out*. Making this information editable by the student would allow some interesting learning to take place by trying to find the smallest set of principles that can be used to analyse the circuit successfully.

Qualitative Explanations If this is to be done then qualitative reasoning about circuits is needed[4]. In the case where the behaviour of each component has been predefined, the standard quantitative account can be supplemented with a qualitative account. If the student is to define various arbitrary relations between the properties of an object then it will be necessary either to derive the component models from the relations or, more plausibly, get the students to define them. One way or another, the qualitative analyser will occasionally need help from the quantitative analyser.

The whole qualitative modelling enterprise needs to be examined from the point of view of student modellers. There are some outstanding questions. Do students run a qualitative model? Are some misconceptions due to a failure to keep the principles of *no function in structure* and *local causality* [de Kleer & Brown 83]?

Adding Analogical Explanations This is an important issue. If a number of analogical systems can be set up —say, a model of a hydraulic system, the teeming crowds of Gentner and Gentner [Gentner & Gentner 83] and a kinetic gas model *and* it is possible to see how to model each of the parts in a qualitative way then there is some reason to hope for good explanations. It is consistent with this discussion to consider providing the opportunity for modellers to edit the details of the analogy.

[4]See section 6.4.2 for a brief description of recent work which has tried to generate explanations based on qualitative reasoning.

6.4 Related Areas: Implications for Further Work

There are a number of potentially fruitful research areas that might contribute to an extension of the work. Some of these are now assessed in order to reach a conclusion about which is likely to be the most promising way forward over the next few years. Here, the discussion focusses on recent work on the development of qualitative physics and the use of simulations in teaching/training. It is argued that some aspects of the use of simulations are likely to pay dividends most quickly.

6.4.1 Work on Qualitative Physics

There is a growing interest in qualitative modelling in the AI community. Important work has been done by de Kleer [de Kleer & Brown 84, de Kleer 84], Forbus [Forbus 84, Forbus 86], Kuipers [Kuipers 84], Raiman [Raiman 86] and Williams [Williams 86]. Those interested in qualitative modelling profess a belief that their ideas permit the modelling of a wide range of scientific misconceptions yet most of their work has been aimed at capturing the qualitative reasoning of the expert rather than the naive person.

Two basically different approaches to the construction of a qualitative physics are now assessed for their likely long term contribution.

Qualitative Process Theory

Forbus has promoted a qualitative process theory (QP) [Forbus 84]. He states that

> Qualitative Process theory concerns the form of dynamical theories, not their specific content

He examines the idea that his theory specifies a language in which certain commonsense physical models can be written

This evokes a scenario in which students model some situation which the system then represents in the QP framework. The system now uses the QP machinery to provide a qualitative description of the behaviour of the model.

This hope is not likely to be fulfilled in the near future. At present, QP theory is poorly defined and a great deal of work is needed to generate a complete representation of some reasonably simple situation. It will be some time before there is a possibility of students building runnable models of their own understanding using the representation language described by Forbus.

The Qualitative Physics of de Kleer

In contrast to Forbus, de Kleer provides a device-centred approach —principally within the system dynamics framework [de Kleer & Brown 84]. Although Forbus regards his process-centred approach to be quite distinct, much of what follows can be applied to certain aspects of QP theory.

De Kleer has analysed how the behaviour of electrical circuits can be deduced from their structure [de Kleer 84]. He uses a method of *qualitative* analysis to derive the set of possible behaviours of a mechanism [de Kleer & Brown 84]. This method is principally an attempt to provide a qualitative analysis analogous to quantitative analysis for system dynamics models.

There are two aspects that are relevant here: whether students could manage to build the kind of models of devices described by de Kleer and whether the approach can be used to provide automatically generated explanations of causal behaviour [de Kleer & Brown 84].

Could Students Manage Qualitative Modelling? The idea of a student reconstructing the mechanisms used to derive a description of behaviour seems too hard —and this makes modelling the misconceptions about circuit behaviour difficult.

It is easier to construct the device topology and the component models. The observations with ELAB suggest that students can handle the construction of the device topology with some success. This leaves us with the question as to whether they can handle the qualitative modelling of components. This is open to further investigation. Yet, if we wish to allow students to express their beliefs about electrical objects, we must be sure that they can all be expressed easily within this framework. This requirement effectively rules out any further consideration of this approach in the short term.

Causal Explanations of Behaviour The automatic generation of causal explanations is a desirable facility for an extended version of ELAB. Nevertheless, Hollan has criticised the use of de Kleer's work to generate causal explanations on three grounds: that people use quasi-quantitative reasoning in addition to pure qualitative reasoning, that qualitative modelling underdetermines the physical behaviour and that people often transgress the principles such as *no function in structure* that have been carefully built into de Kleer's approach [Hollan et al 84].

Raiman has provided a line of attack that might mitigate the first criticism by adding *order of magnitude reasoning* [Raiman 86]. The second criticism can be mitigated but the third criticism is serious in that a response depends on psychological rather than technical criteria. There is no simple solution as to how to present a causal explanation based on qualitative reasoning.

6.4.2 Approaches Based on Simulation

There has been renewed interest in the management of the learning process in which some physical device is to be managed or repaired [Hollan et al 84, White & Fredericksen 84, Woolf & Blegen 86]. The student, however, does no modelling but tries to solve various problems posed by the system.

The ideas underlying these systems become relevant if a special mode of use can be provided for a modelling environment. A fault can be inserted into the model that the student has built (or been provided with). The student has then to debug that model. The development of such ideas is a long term research issue. For example, there is little point in inserting totally arbitrary faults. The development of an intelligent fault injector might sensibly be undertaken for a domain-specific modelling environment —in the case in which a single model is under consideration then the task is simplified but in a (more general) modelling environment the difficulties are likely to increase with the generality.

Even if fault injection could be provided then it is still an open question as to how to improve debugging/fault finding skills. Recent work by White and Fredericksen has sought to capitalise on de Kleer's ideas by introducing students to different levels of qualitative circuit analysis [White & Frederiksen 85, White & Fredericksen 84, White & Fredericksen 86].

One problem that all such systems have might be termed the *expert* paradox. That is, the expert can provide an explanation that is complete. It covers all the important points and so on. It works reasonably well if the student is supposed to be a replica of the expert except for a few facts that are not available. Unfortunately, users who have severe misconceptions are given no guidance whatsoever as to how to attain this understanding from *their current position*. Anecdotal evidence suggests that this is a common mistake made by many human tutors. What is needed is an explicit theory of how to provide the correct steps through which the student should go. White and Fredericksen, for example, point out how difficult it is for students to understand the concept of potential difference but they do not seem to provide any well motivated way to come to a good understanding. To help students understand the concept of potential difference they may well need to find that this concept *emerges* as a necessary part of the explanation of circuit behaviour. This might arise from observation or from simple models but has the great virtue that the need for the concept is met before the name of the concept.

There is another way in which simulations could be used. Assume that we have a set of the well-known buggy models of electrical behaviour. Then we can present a student with a window onto the behaviour of the buggy model applied to a given circuit and a window onto the correct behaviour. The main problem that needs to be solved would seem to be how to choose appropriate circuits. If this is left to the students then a slightly buggy model might still result in reasonably plausible behaviour. Even so, provided the system can reason about the differences in behaviour between the correct model and the buggy one then it could draw attention to these differences[5].

6.5 Educational Implications

6.5.1 Problems Relating to Current Educational Research

It is maintained that the work of a number of educators who are interested in accounting for misconceptions is difficult to build upon directly even though there are some strong similarities between their descriptions and the one presented here.

It has already been pointed out in chapter one that there has been a great deal of interest in the description of students' misconceptions on the part of science educators. There has also been a strong interest in accounting for how these misconceptions arise —there is a belief that it is necessary to look at the phenomenological experience of children in order to make any headway.

Alternative Frameworks

The sense of the research into *Alternative Frameworks* has already been described in section 1.4.4. The fundamental idea is that beliefs that students hold about the physical world that have been derived through their experience interact with the formal physics with which they are presented [Driver & Easley 78].

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[5]See [Looi & Ross 86] for a brief summary of the various methods of reasoning that might be useful.

The studies that have been done often refer to the patterns in children's usage of language. For example, there is the study by Watts which indicates different conceptions of force [Watts 83]. He gives eight different frameworks. Here is not the place to look at these frameworks in detail but one or two things are worth pointing out in regard to his work in particular.

Firstly, he deliberately aimed at an analysis which produces a small number of alternative frameworks. The intention is to avoid having a different framework for each student. This partly undercuts the interests of those who want to be able to construct student models. On the other hand, such an analysis may well be a necessary step in the production of teaching strategies that might be of use in some Intelligent Teaching System (ITS).

The ways and means by which forces are believed to act form a very rich and diverse pattern when students try to explain situations. These patterns fall well outside the approved descriptions of physical processes involving forces.

If students are to be given the ability to model physical situations then it is not necessary to provide interfaces to the formal modelling language that fit any specific alternative framework. It should be enough to provide a language general enough to permit the students to express their beliefs about the rôles that certain processes have —provided that they can interpret their model in the way that suits them. Thus, there is a way of testing ideas about modelling misconceptions: identify students who can be loosely classified in terms of some framework, give them a proposed modelling language and investigate how well they manage to express themselves.

Attempts to Construct a Naive Theory of the World

Hayes has pointed out the basic difficulties in providing a realistic and detailed computational account of physical events [Hayes 79]. Forbus has tried to carry forward some of Hayes' ideas but he has a long way to go before his account really tackles the problems discussed by Hayes —see [Forbus 84]. Meanwhile, some interest has been aroused in the world of the science educators inspired by the ideas of Hayes and others. In particular, Ogborn has begun to develop the idea of support mentioned by Hayes [Hayes 79, Ogborn 85]. He is also interested in ways that computers might assist students make their views of support explicit. Law, Ogborn and Whitelock are attempting to elicit and formalise students' beliefs about dynamics [Law et al 86]. They hope to use an *expert system shell* called APES to conduct a dialogue with the students but the work has only started recently. The likelihood of significant progress in the automation of this task is low. Knowledge elicitation is difficult even for experts trying to represented the knowledge contained within an easily formalised domain. Consequently, students' conceptions of real world phenomena may be too deeply engrained —to the point where they are unable to 'decompile' many of their beliefs.

6.5.2 An Alternative Approach

In the educational research literature there is frequent comment about the similarity between student's misconceptions and previous scientific theories. For example, Osborne and Freyberg quote a nineteenth century explanation by Ampère of the behaviour of electricity in a simple circuit that matches well with their own *clashing currents* model [Osborne & Freyberg 85]. They also have some evidence concerning the nature of the distribution of this misconception amongst students in the range from ten to about eighteen years of age.

Similar statements have been made by a variety of workers about the nature of misconceptions about simple dynamics. These include diSessa, Clements, McCloskey and Viennot [diSessa 82, Clement 83, McCloskey 83, Viennot 85].

Parallels of this kind are often suggested to justify a particular approach to *scientific epistemology.* That is, students' scientific understanding recapitulates the development of scientific ideas through recent history.

On this assumption students would be expected to start with a variant of Aristotle's theories of motion, then develop an impetus theory before arriving at a Newtonian theory.

If a commitment is now added to teaching through confrontation then a teaching program is defined: identify the current theory held by the student, determine its weaknesses, devise experiments for which the student's theory predicts observations in conflict with those of the 'correct' theory and require that the student explore and explain these differences in some way.

There is, however, a major difficulty with identifying the 'current theory'. In order to simplify teaching practice it is necessary to provide a fixed, small set of possible theories. The teacher has to make the decision as to which theory is owned by which student. There are several practical difficulties:

- The teacher may be forced to design learning experiences and/or course material to confront the 'best' alternative theory for the class. The best may be the median alternative theory in which case the teacher has to know the current beliefs for the whole class. In practice, teachers may be guided by statistical evidence of the form provided by Osborne and Freyberg regarding the age distribution of certain theories [Osborne & Freyberg 85].

- In order to provide individualised learning experiences, the teacher may have to make many assessments of the current theory held by each student —it may well be difficult to keep in touch with the student's development.

- Even if it is possible to identify which of the possible alternative theories that the student possesses then it will prove difficult to find the variations of the basic theory actually held by the student.

The approach recommended here is potentially more flexible. Students are provided with modelling facilities which enable the construction of a high level description of their current beliefs. The system has to convert the high level description into a runnable program which can perform the required simulation. A mechanism is then needed that can compare the student's high level description with some standard description of the 'correct' theorem.

From the set of differences it might be desirable for the system to construct a set of experiments that will yield differences in observations between the two theories. If the system is able to suggest problems that the student might wish to solve then the student can be confronted with evidence contradictory to the student's beliefs.

The advantages that such a modelling approach brings include:

- The model built by the student can, as a first approximation, be regarded as the current theory that the student holds.

- The system can handle changes in the student's model.

6.6 Summary

In chapter one, the basic concerns of the thesis were expressed. These can now be summarised as:

Modelling: The advantages and disadvantages have been discussed in general terms and, in the specific sub-domains of physics that were selected, investigated in detail. In practice, students were often found to have had little opportunity to experience the implications of theoretical models or to build models for themselves.

Environments: A number of modelling environments were considered in the design of both DYNLAB and ELAB. Certain trade-offs were required to meet the specific needs of secondary school students. Specialisation of a general-purpose modelling language can, for example, save time in learning a new system.

Misconceptions: Research into students' beliefs about science concepts indicated a wide number of deeply rooted misconceptions. Few, if any, have addressed the problem of encouraging students to make their beliefs explicit in a modelling language/system in order to promote a confrontationist learning strategy.

Chapter two provided an account of the underlying methodology for the remainder of the work. Although the methodology used was adequate for the work described later, further work is needed to expand the range of misconceptions that can be handled in both DYNLAB and ELAB. This work would involve the construction of structured interviews and the corresponding protocol analysis. Further in the future, there is some scope for a summative evaluation of the educational benefits.

Chapters three, four and five detail the design, application and critique of three systems built during the course of the work. ROCKET, the first environment, was initially based on the work by diSessa on a game called TARGET [diSessa 82]. The fundamental idea was to investigate the contention that interaction with a simulation could provide the insight into student's misunderstandings that is needed by both the student and the teacher. In order to make the students' thinking explicit, ROCKET was equipped with both an interactive and a programming mode. In practice, both modes were found to provide a channel of communication which yielded little direct insight into the high level cognitive structures that are involved in the problem solving exercise. This observation supported the belief that students needed a modelling environment to make their own beliefs explicit.

Both DYNLAB and ELAB were designed to promote the explicit modelling of beliefs, to provide students with the opportunity to see how their models function and to work through the process of constructing a more reliable understanding. The designs of each of these environments were strongly based on both known problems in teaching or learning the subject matter and the range of misconceptions known to be held by students. The designs of both systems and details of how they were used by students were given in chapters four and five.

DYNLAB proved to be a useful environment for analysing a reasonable range of dynamics problems —both in terms of declarative and procedural knowledge about dynamics. Preliminary work with the students confirmed that they held many of the relevant dynamics/kinematics misconceptions. Some, but not all, of the students' misconceptions could be modelled. Further work could be undertaken with DYNLAB to explore, for example, misconceptions relating to Newton's third law —both in static and dynamic situations.

ELAB provided the facilities required to represent fairly simple DC and AC circuits. Work with S4 and S5 students on DC circuits yielded a rich source of information about the kinds of problems that they were having with their understanding of simple circuits. Again, preliminary work confirmed the existence of a number of well known misunderstandings about electrical circuits. Further work can be undertaken to investigate AC circuit concepts using ELAB and the system can be developed to handle the explicit modelling of a wider range of problems.

The current chapter has covered the contributions of the thesis at a lower level of detail than found in this summary. In addition, it has outlined both short term developmental work that can be applied to ELAB to produce a more flexible environment and long term research that might be usefully undertaken to give students the ability to express themselves more completely, to provide the modelling environment with the means to monitor the student and to explain the model's behaviour in an appropriate way.

The contribution that recent work on qualitative physics and on the use of simulations was examined. Research on qualitative physics was found to be in a state which does not lend itself readily to the representation of students' buggy models. At the moment, the most fruitful contribution is likely to be a general mechanism for providing causal explanations. A consideration of the uses of simulations suggested that a productive extension would be the addition of a fault injection mode.

The research programme that might sensibly be derived from this work includes:

Confronting Circuit Behaviour Misconceptions The discussion in section 6.2 indicates the general approach. The design for ELAB can be extended along the lines discussed. The system might sensibly be relocated in a Smalltalk-like environment. A suitable misconception test can be designed and the same methodology applied to determine the utility of the approach in confronting the various misconceptions that students hold about electrical behaviour.

Application to Other Domains The fundamental approach can also be applied to a range of other physical phenomena —such as heat flow, water flow, aspects of light and so on. As indicated in section 1.4.5, there is a rapidly growing source of information about a wide range of misconceptions about such processes which can be utilised.

Explanations Using Multiple Models The importance of good explanations of electrical circuit behaviour has been emphasised. White and Fredericksen have already produced a system that can provide explanations in terms of a series of models [White & Fredericksen 86]. Although these models provide for alternative analyses of electrical behaviour, only a single method of analysis is used at any one time. A promising line is therefore to develop the ELAB design to orchestrate these multiple forms of automatic analysis to provide explanations. Further work on explanation facilities includes integrating results from (quantitative and/or qualitative) analysis together with interactions between electrical and other systems and lower level electrical behaviour.

A 'Fault' Diagnosis Mode An environment like ELAB can be provided with a fault diagnosis mode. In this case, the aim would be to detect a fault — but not necessarily in a component of the circuit. Faults might be inserted, for example, into a model of electrical behaviour. Such a system could be tried out with students in a manner such as that suggested by Burton's work with DEBUGGY [Burton 82]. A major part of this work would be an attempt to provide a principled means of fault injection. This work would make use of the electrical misconceptions described in the previous chapter.

The main contribution of the thesis has been: to provide a methodology for confronting science misconceptions, to produce further evidence for the widespread nature of fundamental misconceptions, to demonstrate that modelling provides some (partial) solutions and to outline the ways in which such work might be developed in order to provide more powerful learning environments. In addition, the work has been placed in the context of the educational process and it has been shown that the modelling approach provides advantages that cannot as easily be provided by the classroom teacher.

Bibliography

[Archenhold 75] W.F. Archenhold. *A Study of the Understanding by Sixth Form Students of the Concept of Potential in Physics.* Master's thesis, University of Leeds, 1975.

[Arons 77] A.B. Arons. *The Various Language.* Oxford University Press, New York, 1977.

[Arons 82] A. B. Arons. Phenomenology and logical reasoning in introductory physics courses. *American Journal of Physics*, 50(1):13–20, 1982.

[Arons et al 81] A. Arons, A. Bork, B.L. Kurtz, and F. Collea. Science literacy in the public library — batteries and bulbs. National Educational Computing Conference, 1981.

[Ausubel et al 78] D.P. Ausubel, J.D. Novak, and H. Hanesian. *Educational Psychology: A Cognitive View.* Holt, Rinehart and Winston, New York, 1978.

[Avons et al 81a] S.E. Avons, M.C. Beveridge, A.T. Hickman, and G.J. Hitch. *Contributions of a Concurrent Visible Simulation and Verbal Speed Labels.* Technical Report, Department of Education and Department of Psychology, Manchester University, 1981.

[Avons et al 81b] S.E. Avons, M.C. Beveridge, A.T. Hickman, and G.J. Hitch. *Effects of Spatial Correspondence and An Experimental Study. Degree of Interaction.* Technical Report, Department of Education and Department of Psychology, Manchester University, 1981.

[Beeson 77] G.W. Beeson. Hierarchical learning in electrical science. *Journal of Research in Science Teaching*, 14:117–128, 1977.

[Bell 81] B.F. Bell. What is a plant? some children's ideas. *New Zealand Science Teacher*, 31:10–14, 1981.

[Black 62] M. Black. *Models and Metaphors.* Cornell University Press, New York, 1962.

[Bleaney & Bleaney 57] B.L. Bleaney and B. Bleaney. *Electricity and Magnetism.* Oxford University Press, 1957.

[Bloomer 76] J. Bloomer. *TRICIT —An Electrical Circuit Game. Teacher's Guide.* Technical Note 58, IBM Scientific Centre, Peterlee, 1976.

[Bobrow & Stefic 83] D.G. Bobrow and M. Stefic. *The LOOPS Manual.* Xerox Corporation, 1983.

[Bobrow & Winograd 77] D.G. Bobrow and T. Winograd. An overview of KRL, a knowledge representation language. *Cognitive Science*, 1(1):3–46, 1977.

[Bork 78] A. Bork. Computers as an aid to increasing physical intuition. *American Journal of Physics*, 46(8):796–799, 1978.

[Bork et al 82] A. Bork, S. Franklin, R. Von Blum, D. Trowbridge, and B.L. Kurtz. Science literacy in the public library. Paper, Association of Educational Data Systems, 1982.

[Borning 79] A.H. Borning. *Thinglab — A Constraint Oriented Simulation Laboratory.* Report SSL-79-3, Palo Alto Research Center, 1979.

[Borning 85a] A.H. Borning. *Constraints and Functional Programming.* Tech Report 85-09-05, Computer Science Department, University of Washington, 1985.

[Borning 85b] A.H. Borning. *Defining Constraints Graphically.* Tech Report 85-09-06, Computer Science Department, University of Washington, 1985.

[Brna 83] P. Brna. *Engineering Science and Dynamics.* Working Paper 141, Dept. of Artificial Intelligence, Edinburgh, 1983.

[Brown & VanLehn 80] J.S. Brown and K. VanLehn. Repair theory: a generative theory of bugs in procedural skills. *Cognitive Science*, 4:379–426, 1980.

[Brown et al 75] J.S. Brown, R.R. Burton, and A.G. Bell. SOPHIE: a step toward creating a reactive learning environment. *International Journal of Man-Machine Studies*, 7:675–696, 1975.

[Bruner 66] J.S. Bruner. *Towards a Theory of Instruction.* Harvard University Press, 1966.

[Bullock 79] B. Bullock. The use of models to teach elementary physics. *Physics Education*, 14:312–317, 1979.

[Bundy et al 79] A. Bundy, L. Byrd, G. Luger, C. Mellish, R. Milne, and M. Palmer. *MECHO:A Program to Solve Mechanics Problems.* Working Paper 50, Dept. of Artificial Intelligence, Edinburgh, 1979.

[Burton 82] R.R. Burton. Diagnosing bugs in a simple procedural skill. In D.H. Sleeman and J.S. Brown, editors, *Intelligent Tutoring Systems*, pages 157–183, Academic Press, London, 1982.

[Caillot 84] M. Caillot. L'Intelligence Artificielle au service de la formation. 1984. Paper presented at FORUM EAO 84.

[Caramazza et al 81] A. Caramazza, M. McCloskey, and B. Green. Naive beliefs in sophisticated subjects: misconceptions about trajectories of objects. *Cognition*, 9:117–123, 1981.

[Cawthorn & Rowell 78] E.R. Cawthorn and J.A. Rowell. Epistemology and science education. *Studies in Science Education*, 5:31–59, 1978.

[Chalmers 75] A.F. Chalmers. Maxwell and the displacement current. *Physics Education*, 10:45–49, 1975.

[Champagne et al 80] A.B. Champagne, L.E. Klopper, and J.H. Anderson. Factors influencing the learning of classical mechanics. *American Journal of Physics*, 48(12):1074–1079, 1980.

[Chung 86] P.H.W. Chung. *Teaching Computer Control Applications —A Programming Approach.* PhD thesis, Department of Artificial Intelligence, University of Edinburgh, 1986.

[Clement 82] J. Clement. Students' preconceptions in introductory mechanics. *American Journal of Physics*, 50(1):66–71, 1982.

[Clement 83] J. Clement. A conceptual model discussed by Galileo and used intuitively by physics students. In D. Gentner and A. Stevens, editors, *Mental Models*, Lawrence Erlbaum Press, 1983.

[Cohen et al 83] R. Cohen, B. Eylon, and U. Ganiel. Potential difference and current in simple electrical circuits: a study of students' concepts. *American Journal of Physics*, 51(5):407–412, 1983.

[Collins 79] Collins. *Collins Dictionary of the English Language.* William Collins and Son, 1979.

[Davies 78] B. Davies. Mathematical models in oscillation theory. *Physics Education*, 13:282–286, 1978.

[de Kleer & Brown 80] J. de Kleer and J.S. Brown. *Mental Models of Physical Mechanisms.* Technical Report, Xerox Parc, Palo Alto, 1980.

[de Kleer & Brown 83] J. de Kleer and J.S. Brown. Assumptions and ambiguities in mechanistic mental models. In D. Gentner and A. Stevens, editors, *Mental Models*, Lawrence Erlbaum Press, 1983.

[de Kleer & Brown 84] J. de Kleer and J.S. Brown. A qualitative physics based on confluences. *Artificial Intelligence*, 24:7–83, 1984.

[de Kleer 84] J. de Kleer. How circuits work. *Artificial Intelligence*, 24:205–280, 1984.

[diSessa 77] A. diSessa. *On Learnable Representations of Knowledge: A Meaning for the Computational Metaphor*. LOGO Memo 47, MIT, 1977.

[diSessa 82] A. diSessa. Unlearning Aristotelian physics: a study of knowledge based learning. *Cognitive Science*, 6(2):37–75, 1982.

[diSessa 83] A. diSessa. Phenomenology and the evolution of intuition. In D. Gentner and A. Stevens, editors, *Mental Models*, Lawrence Erlbaum Press, 1983.

[diSessa 86] A. diSessa. 1986. Personal arpanet communication.

[Doran 72] R.L. Doran. Misconceptions of selected science concepts held by elementary school students. *Journal of Research in Science Teaching*, 9:127–137, 1972.

[Driver & Easley 78] R. Driver and J. Easley. Pupils and paradigms: a review of literature related to concept development in adolescent science students. *Studies in Science Education*, 5:61–84, 1978.

[Driver 81] R. Driver. Pupil's alternative frameworks in science. *European Journal of Science Education*, 3(1):93–101, 1981.

[Driver 83] R. Driver. *The Pupil as Scientist?* Open University Press, 1983.

[Ehri & Muzio 74] L.C. Ehri and I.M. Muzio. Cognitive style and reasoning about speed. *Journal of Educational Psychology*, 66:569–571, 1974.

[Ellington et al 81] H.I. Ellington, E. Addinall, and F. Percival. *Games and Simulations in Science Education.* Kogan Page, London, 1981.

[Erickson 79] G. Erickson. Children's conception of heat and temperature. *Science Education*, 63(2):221–230, 1979.

[Evans 78] J. Evans. Teaching electricity with batteries and bulbs. *Physics Teacher*, 16:15–22, 1978.

[Fisher 79] N.J. Fisher. *Identification and Examination of Physics Concepts That Students Find Most Difficult.* Report ERIBC-79:40, ERICB, 1979.

[Forbus 84] K.D. Forbus. Qualitative process theory. *Artificial Intelligence*, 24:85–168, 1984.

[Forbus 86] K. Forbus. Interpreting measurements of physical systems. In *Proceedings of AAAI-86*, pages 113–117, American Association for Artificial Intelligence, 1986.

[Franklin 79] A. Franklin. Galileo and the leaning tower: an Aristotelian interpretation. *Physics Education*, 14:60–63, 1979.

[Fredette & Lockhead 80] N. Fredette and J. Lockhead. Student conceptions of simple circuits. *Physics Teacher*, 18:194–198, 1980.

[Gagné 77] R.M. Gagné. *The Conditions of Learning.* Holt-Saunders, 3rd edition, 1977.

[Gee 78] B. Gee. Models as a pedagogical tool: can we learn from Maxwell? *Physics Education*, 13:287–291, 1978.

[Gentner & Gentner 83] D. Gentner and D.R. Gentner. Flowing waters or teeming crowds: mental models of electricity. In D. Gentner and A. Stevens, editors, *Mental Models*, Lawrence Erlbaum Press, 1983.

[Gilbert & Osborne 80] J.K. Gilbert and R.J. Osborne. The use of models in science and science teaching. *European Journal of Science Education*, 2(1):3–13, 1980.

[Goldberg & Robson 83] A. Goldberg and D. Robson. *Smalltalk-80: The Language and its Implementation.* Addison-Wesley, 1983.

[Gould & Finzer 82] L. Gould and W. Finzer. A study of TRIP: a computer system for animating time-rate-distance problems. *International Journal of Man-Machine Studies*, 17:109–126, 1982.

[Gould & Finzer 84] L. Gould and W. Finzer. *Programming by Rehearsal.* Technical Report SCL-84-1, Xerox Palo Alto Research Center, 1984.

[Hanson 71] N.R. Hanson. *Observation and Explanation.* George Allen and Unwin, 1971.

[Harré 72] R. Harré. *The Philosophies of Science.* Oxford University Press, 1972.

[Harré 78] R. Harré. Models in science. *Physics Education*, 13:275–278, 1978.

[Hayes 79] P.J. Hayes. The naive physics manifesto. In D. Michie, editor, *Expert Systems in the Micro Electronic Age*, Edinburgh University Press, 1979.

[Helm 80] H. Helm. Misconceptions in physics amongst South African students. *Physics Education*, 15(2):92–97&105, 1980.

[Hempel 65] C. Hempel. *Aspects of Scientific Explanations and Other Essays in the Philosophy of Science.* Free Press, New York, 1965.

[Hesse 66] M.B. Hesse. *Models and Analogies in Science.* University of Notre Dame Press, 1966.

[Hogger 84] C. Hogger. *Introduction to Logic Programming.* Academic Press, 1984.

[Hollan et al 84] J.D. Hollan, E.L. Hutchins, and L. Weitzman. STEAMER: an interactive inspectable simulation-based training system. *The AI Magazine*, 5, 1984.

[Holman 75] J. Holman. The use of abstract models in science today. *School Science Review*, 199:391, 1975.

[Howe & du Boulay 79] J.A.M. Howe and B. du Boulay. *Teaching Mathematics through LOGO Programming: An Evaluation Study.* Research Paper 115, Dept. of Artificial Intelligence, Edinburgh, 1979.

[Howe 77] J.A.M. Howe. Developmental stages in learning to program. In F. Klix and J. Hoffman, editors, *Cognition and Memory: Interdisciplinary Research of Human Memory Activities*, North-Holland, Amsterdam, 1977.

[Howe 79] J.A.M. Howe. Learning through model building. In D. Michie, editor, *Expert Systems in the Micro Electronic Age*, Edinburgh University Press, 1979.

[Howe 80] J.A.M. Howe. *Learning Engineering Science in School by Computer.* Working Paper 65, Dept. of Artificial Intelligence, Edinburgh, 1980.

[Howe 81] J.A.M. Howe. *Learning Engineering Science in School by Computer.* Working Paper 99, Dept. of Artificial Intelligence, Edinburgh, 1981.

[Howe 83] J.A.M. Howe. *Learning Engineering Science in School by Computer.* Technical Report, University of Edinburgh, 1983. Final Report to the Social Science Research Council and the Scottish Education Department.

[Howe et al 82] J.A.M. Howe, P.M. Ross, K.R. Johnson, F. Plane, and R. Inglis. Teaching mathematics through programming in the classroom. *Computers in Education*, 6:85–91, 1982.

[Ingalls 78] D. Ingalls. The Smalltalk-76 programming system: design and implementation. Fifth Annual ACM Symposium on Principles of Programming Languages, 1978.

[Johnson 64] P.E. Johnson. Associative meanings of concepts in physics. *Journal of Educational Psychology*, 55:84–88, 1964.

[Johnson 65] P.E. Johnson. Word relatedness and problem solving in high school physics. *Journal of Educational Psychology*, 56:217–224, 1965.

[Johnson 67] P.E. Johnson. Some psychological aspects of subject-matter instruction. *Journal of Educational Psychology*, 58:75–83, 1967.

[Johnson 69] P.E. Johnson. On the communication of concepts in science. *Journal of Educational Psychology*, 60:32–40, 1969.

[Johnstone & Mughol 76] A.H. Johnstone and A.R. Mughol. Concepts of physics at secondary level. *Physics Education*, 11(11):466–469, 1976.

[Johnstone & Mughol 78] A.H. Johnstone and A.R. Mughol. The concept of electrical resistance. *Physics Education*, 13(1):46–49,, 1978.

[Johsua 84] S. Johsua. Student's interpretation of simple electrical diagrams. *European Journal of Science Education*, 6(3):271–275, 1984.

[Jones 86] R.M. Jones. Mac Modeling. *Macworld*, 109–111, September 1986.

[Kass 71] H. Kass. Structure in perceived relations among physics concepts. *Journal of Research in Science Teaching*, 8:339–350, 1971.

[Kowalski 79] R. Kowalski. *Logic for Problem Solving. Artificial Intelligence Series*, North Holland, 1979.

[Kuipers 84] B. Kuipers. Commonsense reasoning about causality: deriving behaviour from structure. *Artificial Intelligence*, 24:169–203, 1984.

[Larkin et al 80] J. Larkin, J. McDermott, D.P. Simon, and H.A. Simon. Expert and novice performance in solving physics problems. *Science*, 208:1335–1342, 1980.

[Law et al 86] N. Law, J. Ogborn, and D. Whitelock. Knowing what the student knows: a use of APES in science education. In *Proceedings of First Annual Conference, PEG-86*, pages 142–145, Prolog Education Group, 1986.

[Leboutet-Barrell 76] L. Leboutet-Barrell. Concepts of mechanics among young people. *Physics Education*, 11(11):462–466, 1976.

[Lewis 86] J. Lewis. STELLA a model of its kind. *Practical Computing*, 66–67, September 1986.

[Linke 75] R.D. Linke. Replicative studies in hierarchical learning of graphical interpretation skills. *British Journal of Educational Psychology*, 45:39–46, 1975.

[Looi & Ross 86] C.K. Looi and P.M. Ross. Automatic program debugging for a Prolog Intelligent Tutoring System. 1986. Forthcoming research report.

[Lovell 74] K. Lovell. Intellectual growth and understanding science. *Studies in Science Education*, 1:1–19, 1974.

[Macfarlane 70] A.G.J. Macfarlane. *Dynamical System Models*. Harrap, 1970.

[Maloney 84] D.P. Maloney. Rule-based approaches to physics: Newton's third law. *Physics Education*, 19(1):37–42, 1984.

[Maxwell 92] J.C. Maxwell. *Electricity and Magnetism*. Oxford University Press, 1892.

[McCleland 75] G. McCleland. Earthly mechanics: two misapprehensions and a heresy. *Physics Education*, 10:128–129, 1975.

[McCloskey 83] M. McCloskey. Naive theories of motion. In D. Gentner and A. Stevens, editors, *Mental Models*, Lawrence Erlbaum Press, 1983.

[McCloskey et al 80] M. McCloskey, A. Caramazza, and B. Green. Curvilinear motion in the absence of external forces: naive beliefs about the motion of objects. *Science*, 5:1139–1141, 1980.

[McCorkindale 80] H.K. McCorkindale. *Engineering Science*. Holmes McDougall, Edinburgh, 1980.

[McIntyre & Reed 76] P.J. McIntyre and J.A. Reed. The effect of visual devices based on Bruner's modes of representation on teaching concepts of electrostatics to elementary school children. *Science Education*, 60(1):87–94, 1976.

[McIntyre 74] P.J. McIntyre. Students' use of models in their explanations of electrostatic phenomena. *Science Education*, 58(4):577–580, 1974.

[Meaden 66] G.T. Meaden. *Electrical Resistance of Metals.* Heyward Books, London, 1966.

[Megarry 77] J. Megarry. CIRCUITRON: an electric circuit game. In J. Megarry, editor, *Aspects of Simulation and Gaming*, Kogan Paul, London, 1977.

[Muetzelfeldt et al 86] R. Muetzelfeldt, A. Bundy, M. Uschold, and D. Robertson. ECO —an intelligent front end for ecological modelling. In E.J.H. Kerckhoffs, G.C. Vandersteenkiste, and B.P. Zeigler, editors, *AI Applied to Simulation*, Society for Computer Simulation, San Diego, California, 1986.

[Nagel & Pederson 73] L.W. Nagel and D.O. Pederson. *Users Guide for SPICE 1.* Department of Electrical Engineering and Computer Sciences, University of California, 1973.

[Nagel 61] E. Nagel. *The Structure of Science.* Routledge and Kegan Paul, 1961.

[Nussbaum & Novak 76] J. Nussbaum and J. Novak. An assessment of children's concepts of the earth utilising structured interviews. *Science Education*, 60(4):535–550, 1976.

[Ogborn 85] J. Ogborn. Understanding students' understandings: an example from dynamics. *European Journal of Science Education*, 7(2):141–150, 1985.

[Ormerod 78] M.B. Ormerod. "Real" models and physical properties. *Physics Education*, 13:278–282, 1978.

[Osborne & Freyberg 85] R.J. Osborne and P. Freyberg. *Learning in Science: The Implications of Children's Science.* Heinemann, 1985.

[Osborne & Gilbert 80a] R.J. Osborne and J.K. Gilbert. A method for investigating concept understanding in science. *European Journal of Science Education*, 2(3):311–321, 1980.

[Osborne & Gilbert 80b] R.J. Osborne and J.K. Gilbert. A technique for exploring students' views of the world. *Physics Education*, 15(6):376–379, 1980.

[Osborne 81] R.J. Osborne. Children's ideas about electric current. *New Zealand Science Teacher*, 29:12–19, 1981.

[Osborne et al 83] R.J. Osborne, B.F. Bell, and J.K. Gilbert. Science teaching and children's views of the world. *European Journal of Science Education*, 5(1):1–14, 1983.

[O'Sullivan 80] C.T. O'Sullivan. Ohm's law and the definition of resistance. *Physics Education*, 15(4):237–239, 1980.

[Page 77] C.H. Page. Electromotive force, potential difference and voltage. *American Journal of Physics*, 45(10):978–980, 1977.

[Papert 71] S. Papert. *A Computer Laboratory for Elementary Schools.* AI Memo 246, MIT, 1971.

[Papert 80] S. Papert. *Mindstorms: Children, Computers, Powerful Ideas.* Harvester Press, 1980.

[Papert et al 79] S. Papert, D. Watt, A. diSessa, and S. Weir. *Brookline LOGO Project. Part 2. Project Summary and Data Analysis.* AI memo 545, MIT, 1979.

[Pask 76] G. Pask. Conversational techniques in the study and practice of education. *British Journal of Educational Psychology*, 46:12–25, 1976.

[Pope 85] P.N. Pope. Analogy between Mechanics and Electricity. *European Journal of Physics*, 6(1):16–21, 1985.

[Preece 76] P.F.W. Preece. Associative structure of science concepts. *British Journal of Educational Psychology*, 46:174–183, 1976.

[Preece 82] J. Preece. *Investigating How Students Interpret Complex Cartesian Graphs.* Technical Report 19, CAL Research Group, Open University, 1982.

[Rae et al 77] G. Rae, T.R. Carnie, E.M. Leonard, J. McCall, and J.M. Wilson. *Acceleration in 'O' Grade Physics.* Technical Report, Aberdeen College of Education, 1977.

[Raiman 86] O. Raiman. Order of magnitude reasoning. In *Proceedings of AAAI-86*, pages 100–104, American Association for Artificial Intelligence, 1986.

[Raven 68] R.J. Raven. The development of the concept of momentum in primary school children. *Journal of Research in Science Teaching*, 5:216–223, 1968.

[Raven 72] R.J. Raven. The development of the concept of acceleration in elementary school children. *Journal of Research in Science Teaching*, 9:201–206, 1972.

[Rieger & Grinberg 77] C. Rieger and M. Grinberg. The declarative representation and procedural simulation of causality in physical mechanisms. In *Proceedings of IJCAI-77*, pages 250–255, 1977.

[Robertson & Richardson 75] W.W. Robertson and E. Richardson. The development of some physical science concepts in secondary school students. *Journal of Research in Science Teaching*, 12:319–330, 1975.

[Rowell & Dawson 77] J.A. Rowell and C.J. Dawson. Teaching about floating and sinking: an attempt to link cognitive psychology with classroom practice. *Science Education*, 61(2):245–253, 1977.

[Rowell 84] J.A. Rowell. Towards controlling variables: a theoretical appraisal and a teachable result. *European Journal of Science Education*, 6(2):115–130, 1984.

[Ruggiero et al 85] S. Ruggiero, A. Cartelli, F. Duprè, and M. Vicentini-Missoni. Weight, gravity and air pressure: mental representations by Italian middle school pupils. *European Journal of Science Education*, 7(2):181–194, 1985.

[Rumelhart & Norman 78] D.E. Rumelhart and D.A. Norman. Accretion, tuning and restructuring: three modes of learning. In J.W. Cotton and R.L. Klatzky, editors, *Semantic Factors of Cognition*, Lawrence Erlbaum, New York, 1978.

[Saltiel & Malgrange 80] E. Saltiel and J.L. Malgrange. Spontaneous ways of reasoning in elementary kinematics. *European Journal of Physics*, 1(2):73–80, 1980.

[SCEEB 76] SCEEB. *Physics: Ordinary and Higher Grades.* Dalkeith, 1976.

[SCEEB 81] SCEEB. *Examination Papers, Higher Physics 1978—1981.* Glasgow, 1981.

[Scriven 74] M. Scriven. Evaluation perspectives and practices. In W.J. Popham, editor, *Evaluation in Education: Current Applications*, McCutchan Publishing Corporation, 1974.

[SEB 82] SEB. *Scottish Certificate of Education Examination: Conditions and Arrangements 1983.* Dalkeith, 1982.

[Shannon 76] B. Shannon. Aristotelianism, Newtonianism and the physics of the layman. *Perception*, 5, 1976.

[Shavelson 72] R.J. Shavelson. Some aspects of the correspondence between content structure and cognitive structure in physics instruction. *Journal of Educational Psychology*, 63:225–234, 1972.

[Shavelson 74] R.J. Shavelson. Methods for examining representations of a subject matter structure in a student's memory. *Journal of Research in Science Teaching*, 11:231–249, 1974.

[Shayer & Adey 81] M. Shayer and P. Adey. *Towards a Science of Science Teaching: Cognitive Development and Curriculum Demand.* Heineman Educational, 1981.

[Shayer 72] M. Shayer. Conceptual demands of the Nuffield 'O' level physics course. *School Science Review*, 54:26–34, 1972.

[Shipstone 84] D.M. Shipstone. A study of children's understanding of electricity in simple DC circuits. *European Journal of Science Education*, 6(2):185–198, 1984.

[Shire 60] E.S. Shire. *Classical Electricity and Magnetism.* Cambridge University Press, 1960.

[Siegel & Raven 71] B. Siegel and R. Raven. The effect of manipulation of the compensatory concepts of speed, force and work. *Journal of Research in Science Teaching*, 8:373–378, 1971.

[Skemp 79] R.R. Skemp. *Intelligence, Learning and Action.* John Wiley and Sons, 1979.

[Smith & Wilson 74] F.A. Smith and J.D. Wilson. Electrical circuits and water analogies. *Physics Teacher*, 12:312–317, 1974.

[Smith 86] R.B. Smith. The alternative reality kit: an animated environment for creating interactive simulations. In *Proceedings of the 1986 IEEE Computer Society Workshop on Visual Languages*, pages 99–106, 1986.

[Soloman 83] J. Soloman. Learning about energy: how pupils think in two domains. *European Journal of Science Education*, 5(1):49–59, 1983.

[Sparkes 82] R.A. Sparkes. Microcomputers in science teaching. *School Science Review*, 63:442–452, 1982.

[Suppe 77] F. Suppe. *The Structure of Scientific Theories.* University of Illinois Press, 1977.

[Sussman & Steele 80] G.J. Sussman and G.L. Steele. Constraints —a language for expressing almost-hierarchical descriptions. *Artificial Intelligence*, 14:1–39, 1980.

[Tiberghien & Delacote 76] A. Tiberghien and G. Delacote. Manipulations et representations de circuits electrique simples chez les enfants de 7 a 12 ans. *Révue Français de Pédagogie*, 34, 1976.

[Trowbridge & McDermott 80] D.E. Trowbridge and L.C. McDermott. Investigation of student understanding of the concept of velocity in one dimension. *American Journal of Physics*, 48(12):1020–1028, 1980.

[Trowbridge & McDermott 81] D.E. Trowbridge and L.C. McDermott. Investigation of student understanding of the concept of acceleration in one dimension. *American Journal of Physics*, 49(3):242–253, 1981.

[Uschold et al 84] M. Uschold, N. Harding, R. Muetzelfeldt, and A. Bundy. An intelligent front end for ecological modelling. In T. O'Shea, editor, *ECAI-84: Advances in AI*, Elsevier Science Publishers, 1984.

[Viennot 79] L. Viennot. Spontaneous reasoning in elementary dynamics. *European Journal of Science Education*, 1(2):205–221, 1979.

[Viennot 85] L. Viennot. Analysing students' reasoning in science: a pragmatic view of theoretical problems. *European Journal of Science Education*, 7(2):151–162, 1985.

[Warren 65] J.W. Warren. *The Teaching of Physics*. Butterworths, London, 1965.

[Warren 79] J.W. Warren. *Understanding Force*. John Murray, 1979.

[Watts 83] D.M. Watts. A study of schoolchildren's alternative frameworks of the concept of force. *European Journal of Science Education*, 5(2):217–230, 1983.

[Watts 85] D.M. Watts. Student conceptions of light: a case study. *Physics Education*, 20(4):183–187, 1985.

[White & Fredericksen 84] B.Y. White and J.R. Fredericksen. Modeling expertise in troubleshooting and reasoning about simple electric circuits. In *Proceedings of Sixth Annual Conference*, pages 337–343, Cognitive Science Society, 1984.

[White & Fredericksen 86] B. White and J.R. Fredericksen. Intelligent tutoring systems based upon qualitative model evolutions. In *Proceedings of AAAI-86*, pages 313–319, American Association for Artificial Intelligence, 1986.

[White & Frederiksen 85] B.Y. White and J.R. Frederiksen. QUEST: qualitative understanding of electrical system troubleshooting. BBN Laboratories, 1985. Appeared in the ACM SIGART newsletter, July 1985.

[White 73] R.T. White. Research into learning hierarchies. *Revue of Educational Research*, 43(3):361–375, 1973.

[White 74] R.T. White. Indexes used in testing the validity of learning hierarchies. *Journal of Research in Science Teaching*, 11(1):61–66, 1974.

[White 81] B.Y. White. *Designing Computer Games to Facilitate Learning.* PhD thesis, MIT, 1981.

[Wilkening 81] F. Wilkening. Integrating velocity, time and distance information: a developmental study. *Cognitive Psychology*, 13:231–247, 1981.

[Wilkinson 73] D. Wilkinson. *A Study of Some Concepts Involving Electricity.* Master's thesis, University of Leeds, 1973.

[Williams 76] D.J. Williams. *A Study of Some Aspects of the Growth in GCE O Level Candidates of the Concept of Momentum.* Master's thesis, University of Leeds, 1976.

[Williams 86] B. Williams. Doing time: putting qualitative reasoning on firmer ground. In *Proceedings of AAAI-86*, pages 105–112, American Association for Artificial Intelligence, 1986.

[Woolf & Blegen 86] B. Woolf and D. Blegen. Teaching a complex industrial process. In *Proceedings of AAAI-86*, pages 722–728, American Association for Artificial Intelligence, 1986.

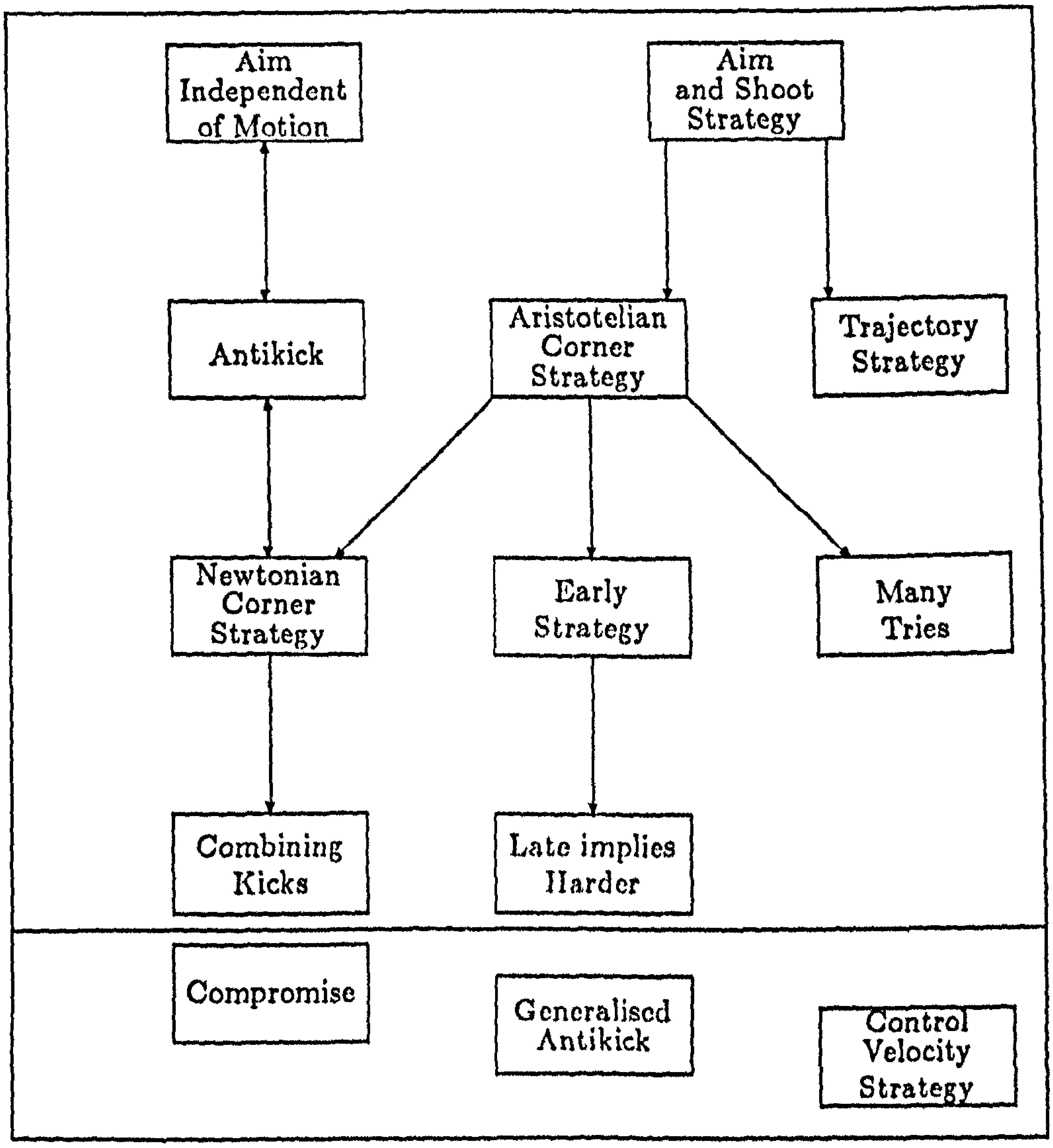
[Wylam & Shayer 80] H. Wylam and M. Shayer. *CSMS Science Reasoning Tasks.* NFER, Windsor, 1980.

[Za'Rour 75] G.I. Za'Rour. Science misconceptions among certain groups of students in Lebanon. *Journal of Research in Science Teaching*, 12:385–391, 1975.

[Zeitman & Hewson 86] A.I. Zeitman and P.W. Hewson. Effect of instruction using microcomputer simulations and conceptual change strategies on science learning. *Journal of Research in Science Teaching*, 23(1):27–39, 1986.

Appendix A

diSessa's Learning Path Chart



Appendix B

Sample ROCKET Worksheets

The following is a selection of the worksheets used with ROCKET.

ROCKET WORKSHEET 4

Program 1
Write this program and then run it.

```
1        RIGHT 18
2        END
```

a) Did the direction of motion change?
b) Did the velocity of the rocket change?

Program 2
Write this program and then run it.

```
1        WAIT 5
2        KICK 6
3        END
```

a) Did the direction of motion change when the rocket was kicked?
b) Did the rocket change velocity?
c) Did the kick make the rocket move in the same direction as the kick?

Program 3
Write this program and then run it.

```
1        RIGHT 18
2        KICK 9
3        END
```

a) What happens to the direction of motion of the rocket?

b) Did the kick change the velocity of the rocket?

c) Did the kick make the rocket move in the same direction as the kick?

d) By rewriting this program with a different line no. 2 make the rocket come to rest.

What did this tell us about the initial speed of the rocket in units of kick?

ROCKET WORKSHEET 5

Program 1

Write this program and then run it.

```
1    WAIT 10
2    RIGHT 9
3    WAIT 5
4    KICK 4
5    END
```

a) Try to describe what happens to the rocket up to the kick.
b) In what direction is the rocket pointing just before the kick?
c) In roughly what direction does the rocket go after the kick?
d) At what speed do you think the rocket is travelling after the kick?
e) Is there a change in the velocity of the rocket?
f) Does the rocket travel in the direction of the kick?

Program 2

Write this program and then run it.

```
1    RIGHT 18
2    WAIT 3
3    KICK 4
4    LEFT 9
5    KICK 4
6    END
```

a) Describe what happens up to the second kick.

b) In what direction is the rocket pointing just before the second kick?

c) In what direction does the rocket go just after the second kick?

d) At what speed is the rocket travelling after the second kick?

e) Did the second kick change the velocity of the rocket?

f) Did the rocket go in the same direction as the direction of the second kick?

ROCKET WORKSHEET 7

Question 1

If a kick of 5 were given to a rocket travelling at a speed of 2 units would the speed (whatever the directions of the rocket and the kick) be:

a) Always 7 b) Sometimes 7 c) Very rarely 7

Program 1

Try the following program

```
1    RIGHT 9
2    KICK 2
3    RIGHT 18
4    KICK 2
5    END
```

a) In what direction is the first kick?

b) In what direction is the second kick?

c) In what direction does the rocket travel before the first kick?

d) In what direction does the rocket travel after the second kick?

e) Is the speed of the rocket after the second kick the same as the speed of the rocket before the first kick?

f) What is the total effect of the two kicks on the velocity of the rocket?

g) Compare your program with

```
1    RIGHT 9
2    RIGHT 18
3    END
```

This program is the same as the one above but with the kicks missing.

Comparing the paths of the rocket for each of the two programs, what was the overall effect of the two kicks on the path of the rocket?

Appendix C

Strategies Modelled for ROCKET

Work on this aspect was not an issue directly addressed in the thesis although some reference has been made to it. It is possible to extend the work to provide more psychologically plausible models of how students solve problems in the ROCKET 'microworld'.

C.1 Possible Heuristics

The following is a list of heuristics that apply to ROCKET derived from White's thesis [White 81]:

1. When two forces are trying to influence the motion of an object the result is a compromise: the object moves in a direction between the two forces —if the two forces are unequal the result will be more towards the direction of the stronger force.

2. If the application of one operator almost works but not quite then try two applications.

3. If a kick causes the rocket to take a path that does not move the rocket through a large enough angular displacement then, next time, apply the kick earlier. This is referred to as "got there late —leave earlier next time".

4. If it is necessary to make a turn to point in a particular direction then reaim by turning the rocket by more than this amount.

5. Experiment with operators to see what happens.

C.2 Possible Plans

Here are comments on possible plans that apply to the corresponding items in the above list:

1. If the intention is to hit the target then find the direction of the target, the heading of the rocket, the direction of motion and the speed and kick the amount that a certain ratio indicates.

2. If the last operator is known and if it is also known that the last operator produced a move closer to hitting the target then reapply the same operator.

3. If a context is remembered which is marked as "got there late" then recover the prior history of operators and cut out some *wait*'s —this must be associated with another plan that indicates when to save a context and what needs to be saved as part of the context. Note that it is *Wait* commands that have to be cut out rather than *Left* or *Right*.

4. If the intention is to hit the target and the rocket is not pointing in that direction then move in such a way as to turn past the target's direction and then kick.

5. If no other plan is appropriate then choose an operator at random.

C.3 Simulated Strategies

There were three classes of strategy that were implemented. Basically, variations on Aristotle Corner, Newton Corner and Early.

Aristotle Corner

Four different models were built. Two for each of *Aristotle Corner(1)* and *Aristotle Corner(2)*. Each of the two variations of the basic strategy were implemented in 'simple' and 'complex' forms. The essential difference was that the complex versions would try to turn the rocket to straddle the target if it wasn't pointing at the target. All versions would only fire, however, if the rocket was judged to be pointing at the target.

Newton Corner

Only one version was implemented. It is given in reasonable detail below. The rules that apply can be paraphrased as:

1. If the rocket is stopped and the rocket is pointing at the target then pick any sized Kick and apply.

2. If the rocket is stopped and the rocket is not pointing at the target then find out which operator of {Left, Right} will be best to apply and apply it.

3. If the rocket is moving and pointing in the opposite direction in which it is going then apply a kick to bring it to rest or, if this is not possible, to as small a value as possible.

4. If the rocket is moving and not pointing in the opposite direction to that of its motion then choose which operator of {Left, Right} will be the best and apply it.

There are a number of non-trivial aspects to this model. Item 2 above hides the details of how to cope with *dithering.* That is, a turn can be made from a nearly good position to another such position but on the opposite side of the target. In this case, it is necessary to apply a Kick and start all over again.

Early

Two implementations were given. One relied on a precise trigonometric rule to find the best sized Kick to apply once the rocket is in the correct context. The other used a simple proportion argument. Both versions produced essentially the same performance over a limited set of tests.

Appendix D

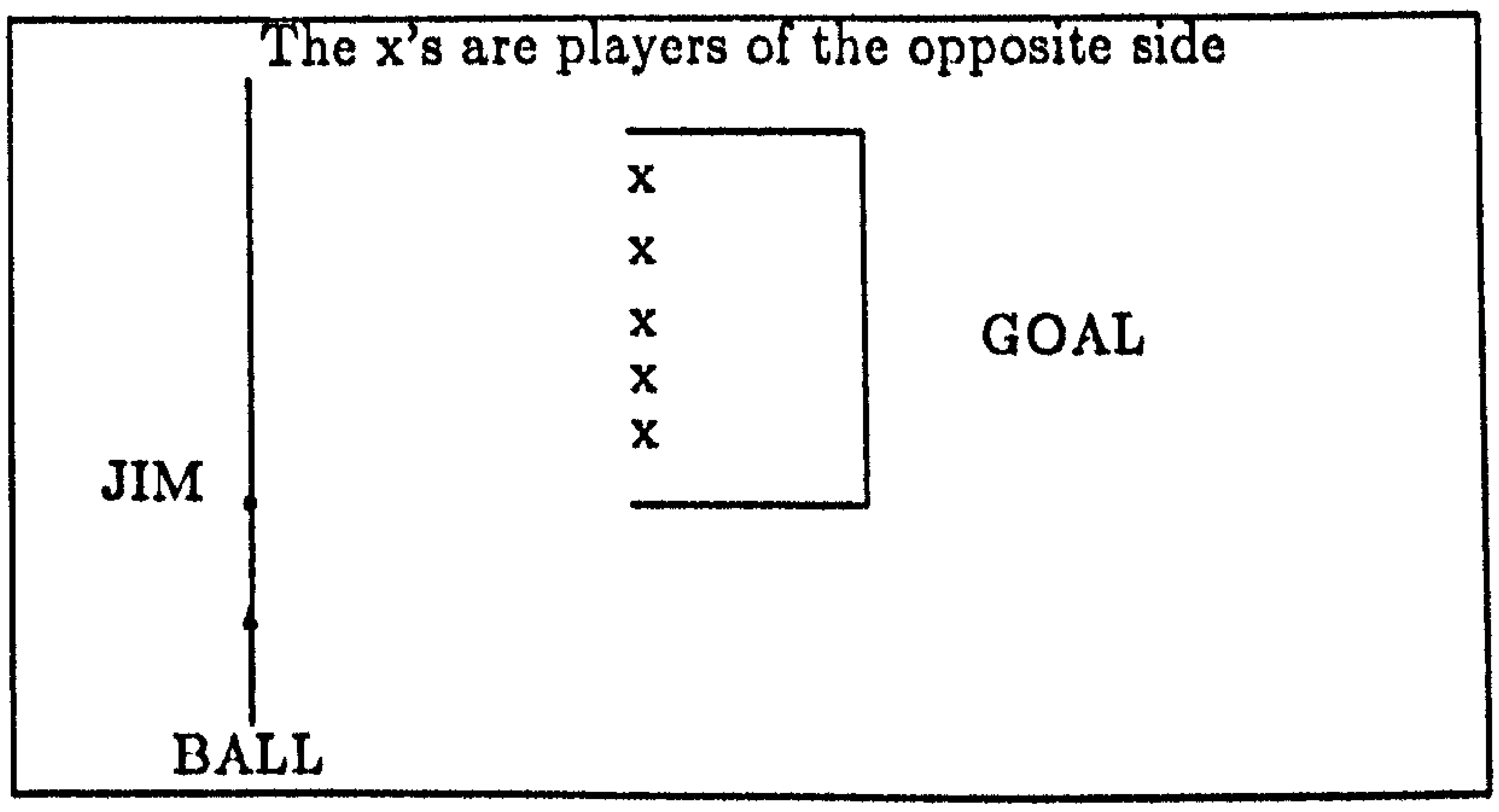
Dynamics Test

You have 40 minutes to answer these questions.

Write all your answers on the question paper.

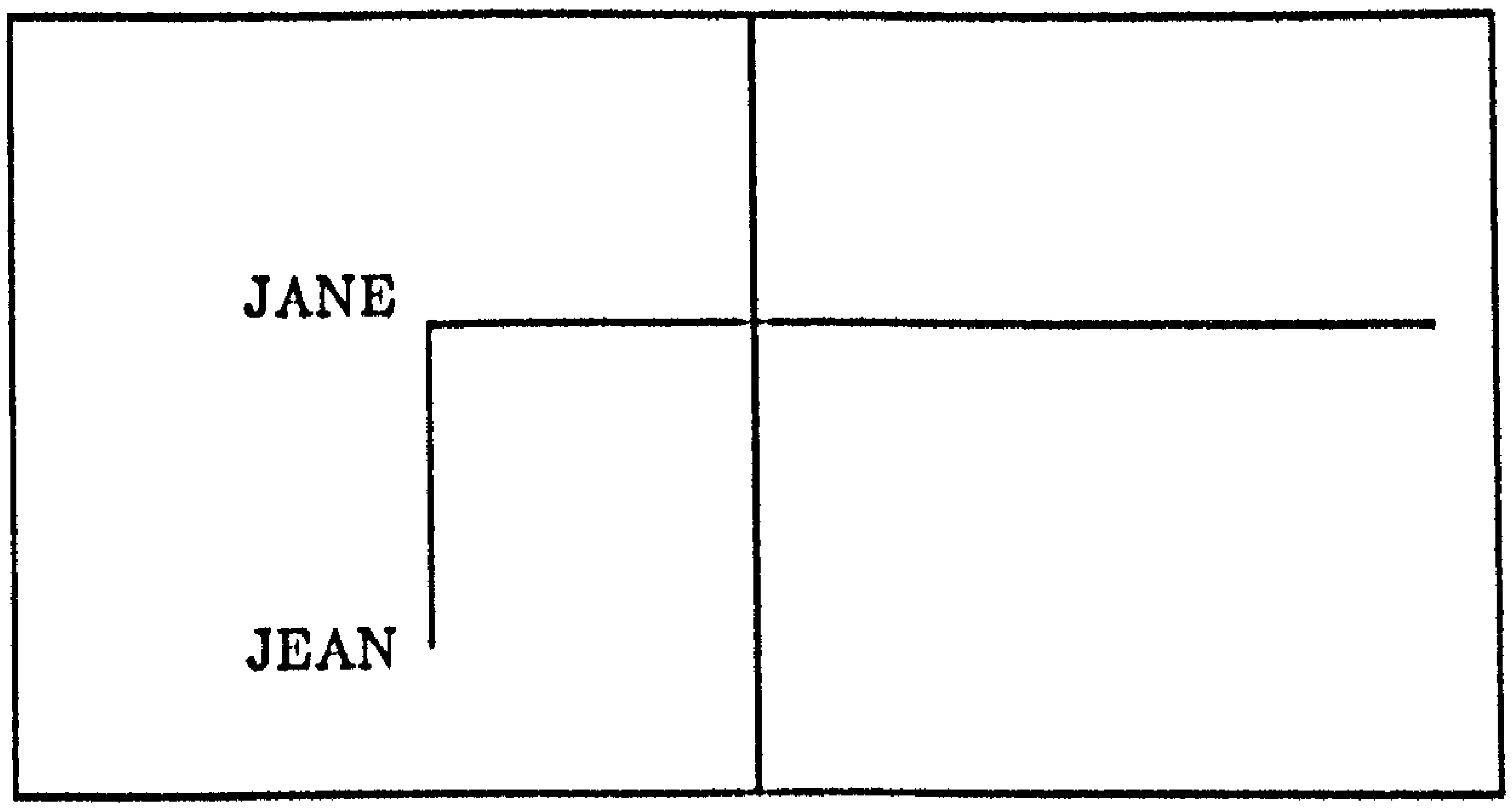
1 Jim is playing football when he receives a fast pass straight across the goal mouth. He wants to hit the ball into the gap at the bottom of the goal.

On the diagram, indicate roughly the direction in which he should strike the ball.

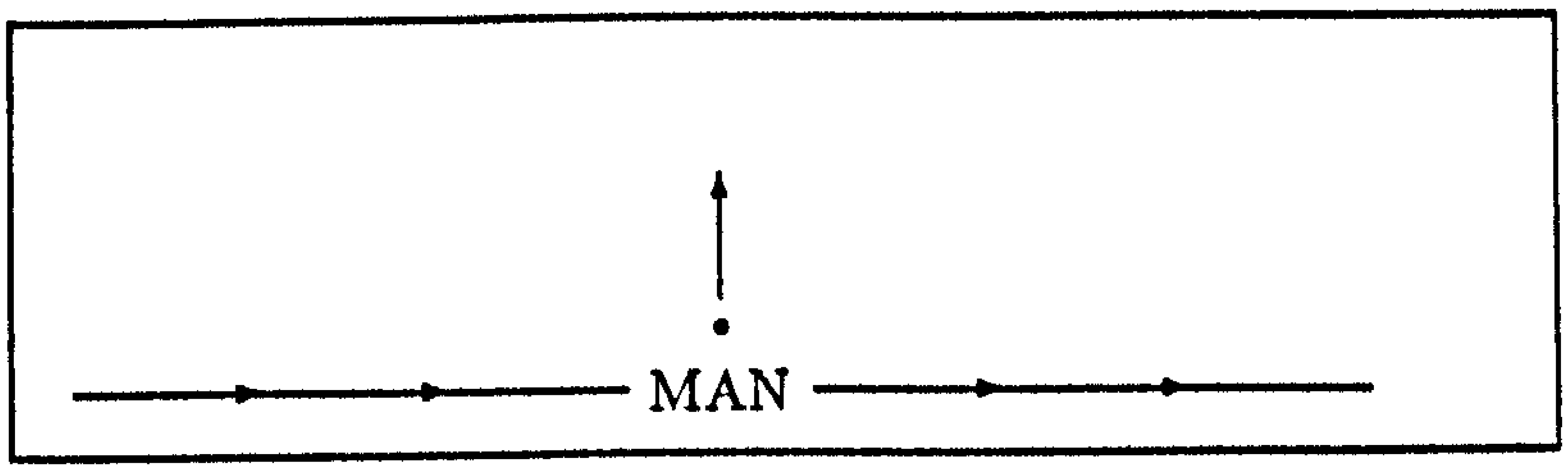


2 Jean is playing volleyball when she receives a pass from Jane parallel with the net.

On the diagram, indicate roughly the direction in which Jane punched the ball.



3 A man stands on a moving walkway and throws a ball vertically into the air.



Indicate which of the following happens:

1. The ball falls behind the man

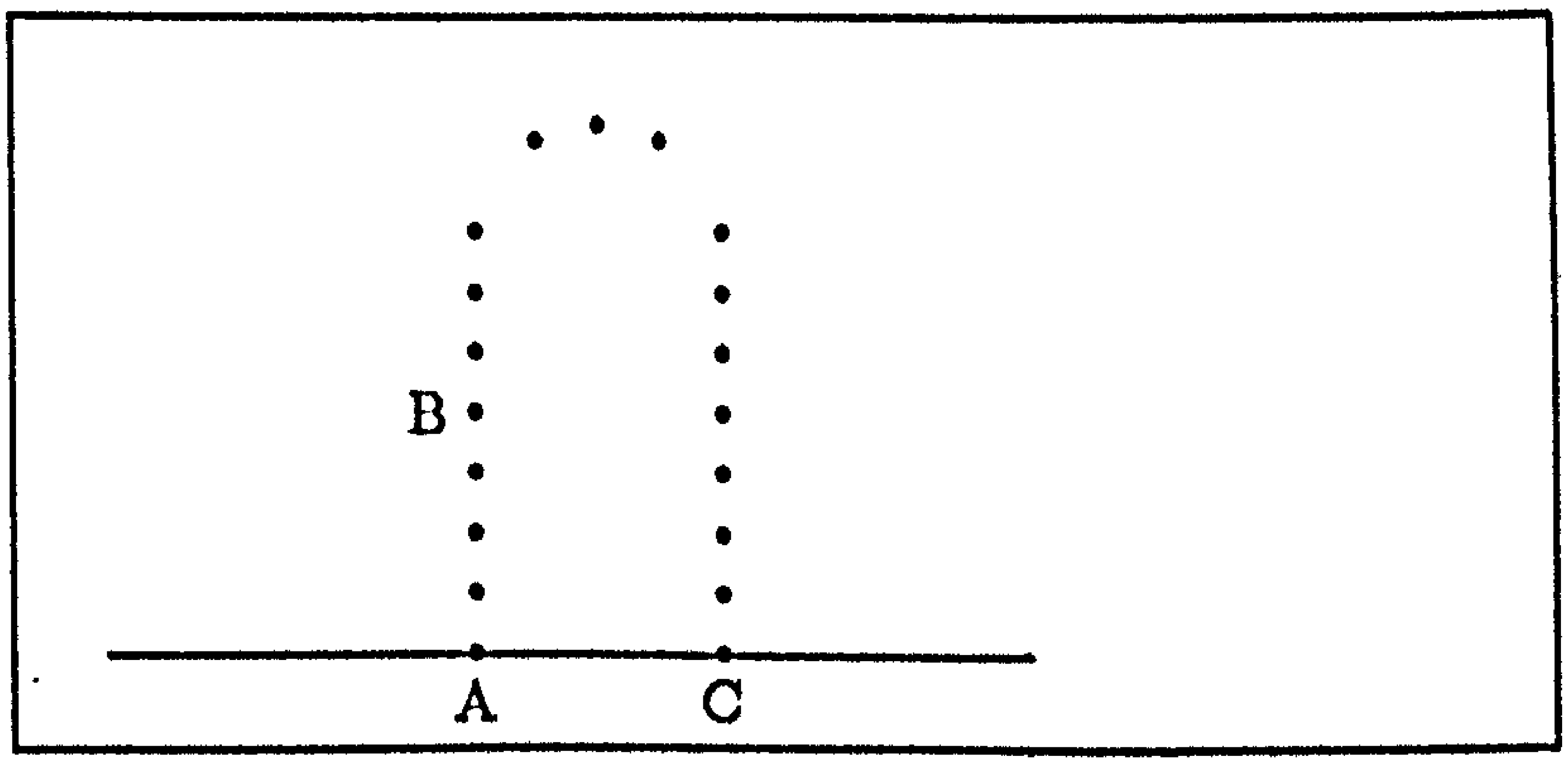
2. The ball comes back to the man

3. The ball lands in front of the man

4 A coin is thrown from point A straight up into the air and caught at C.

On the diagram draw one or more arrows showing the direction of each force acting on the coin when it is at point B.

Draw LARGER arrows for LARGER forces.



5 A rocket is moving sideways in deep space, with its engines off, from point A to point B.

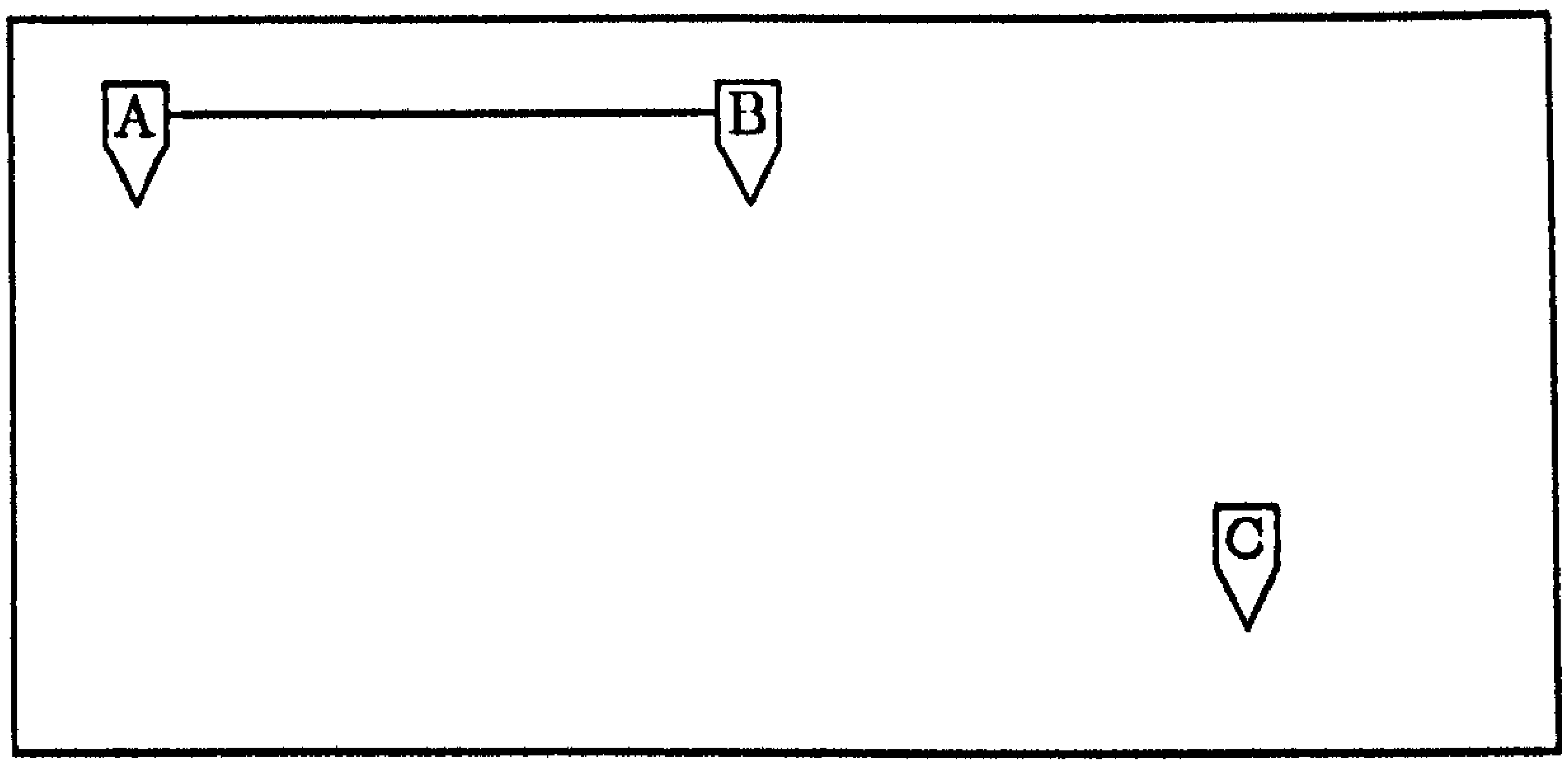
It is not near any planets or other outside forces.

Its engine is fired at point B and left on for 2 seconds while the rocket travels from B to C.

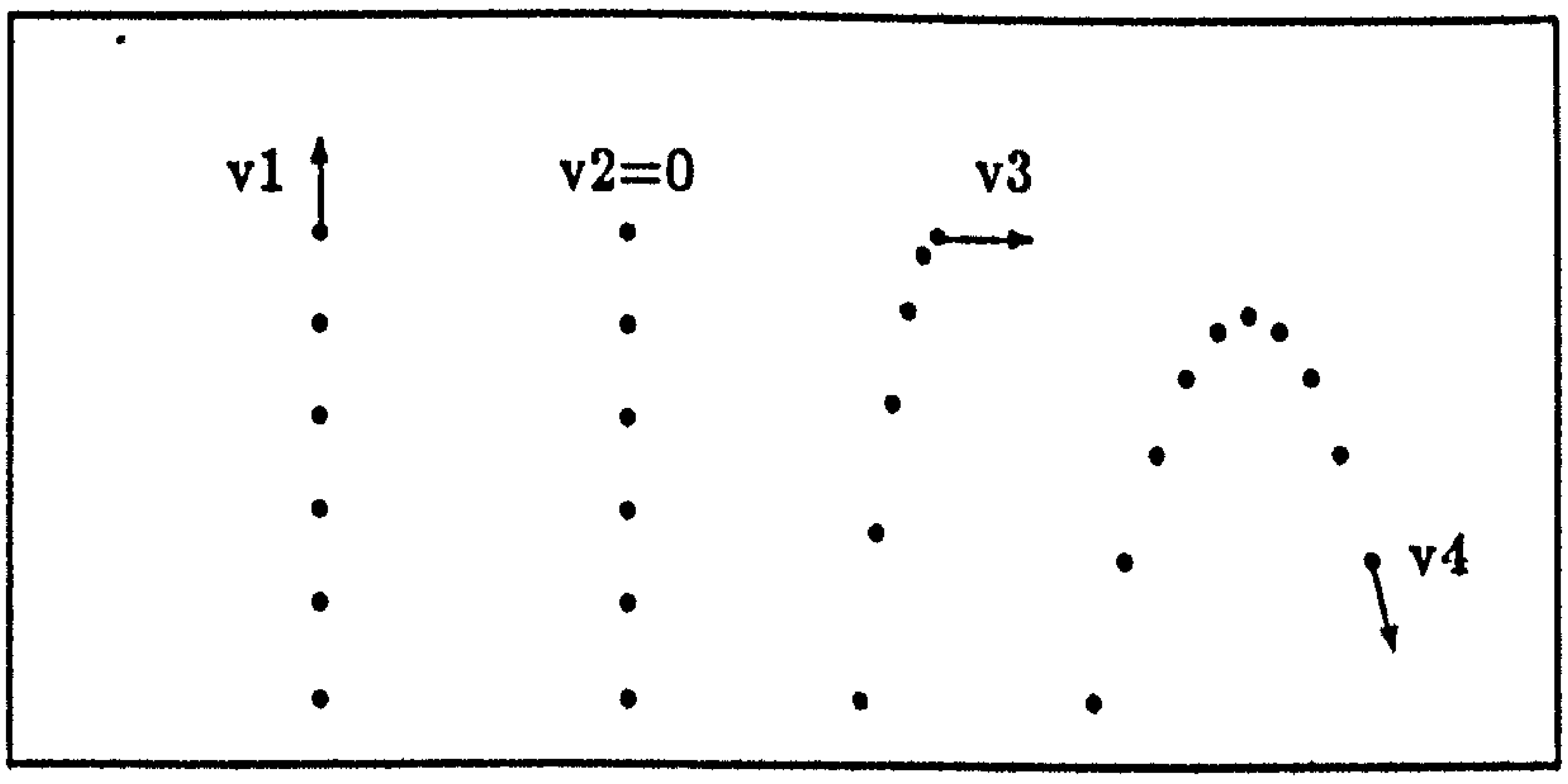
On the diagram, draw in the shape of the path

a) from B to C

b) from C —remember that the engine is turned off now.



6 A juggler throws four balls in the air.

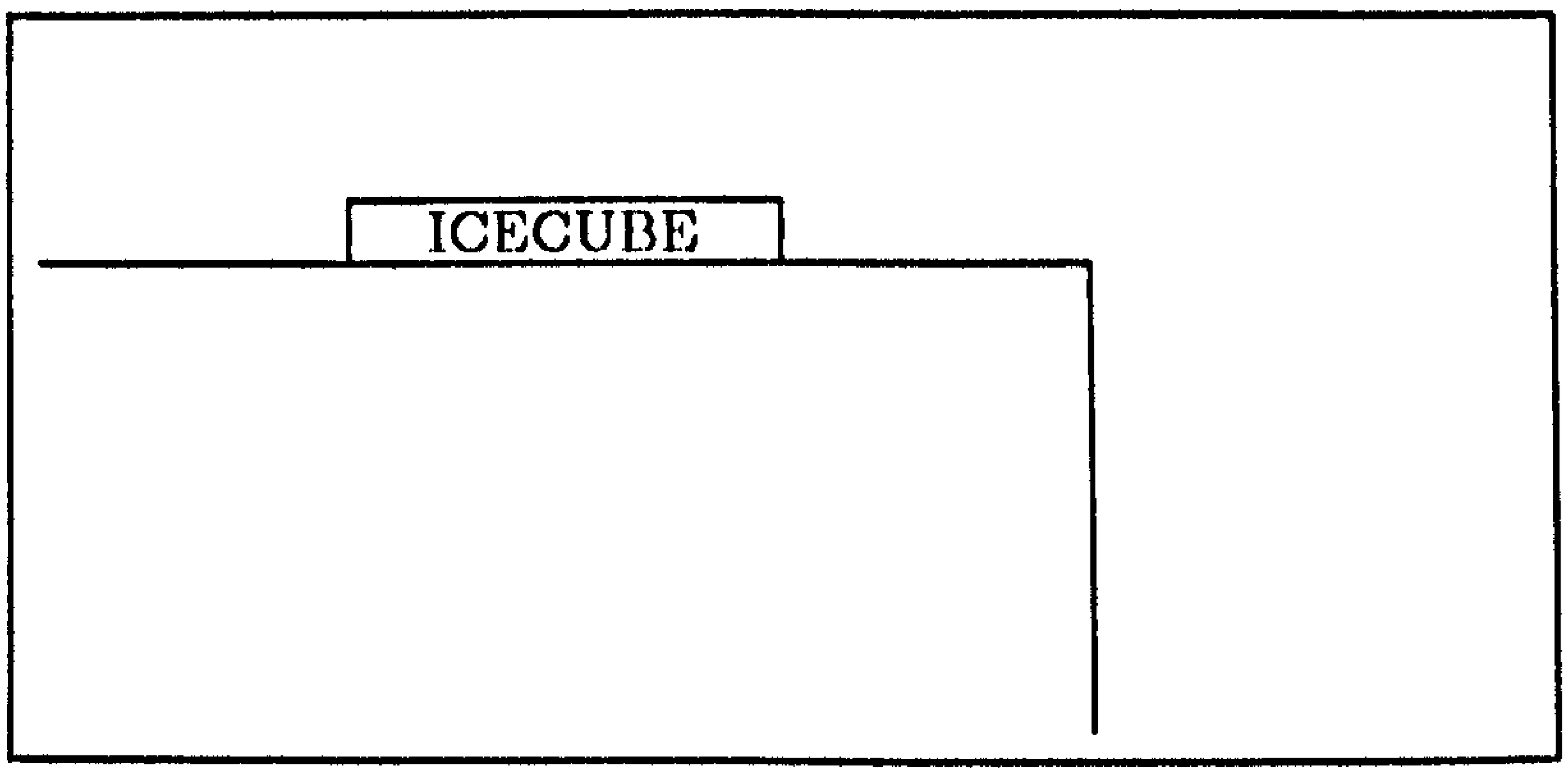


The arrows indicate both the magnitude and direction of the velocities of the balls.

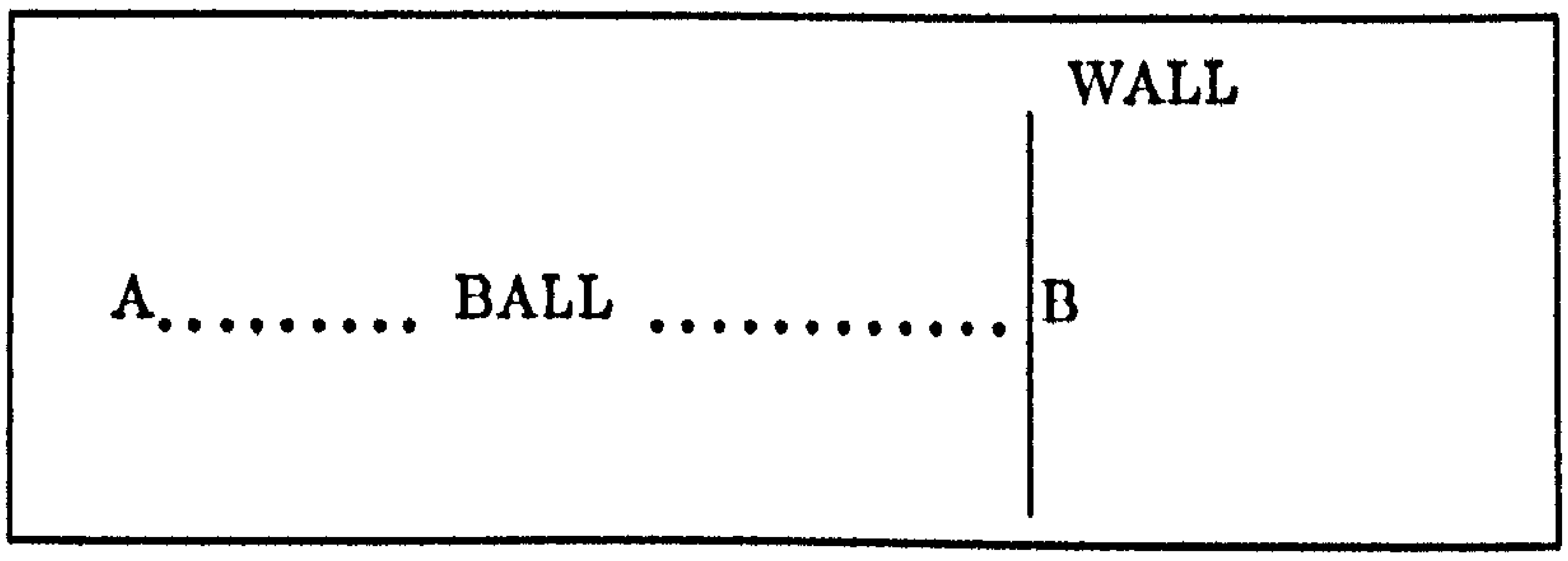
Are the forces acting on the bodies identical? —Answer Yes or No

Give a reason for your answer.

7 An ice cube slides along a smooth table and falls off the end moving fast. On the diagram, indicate the path that the cube takes.

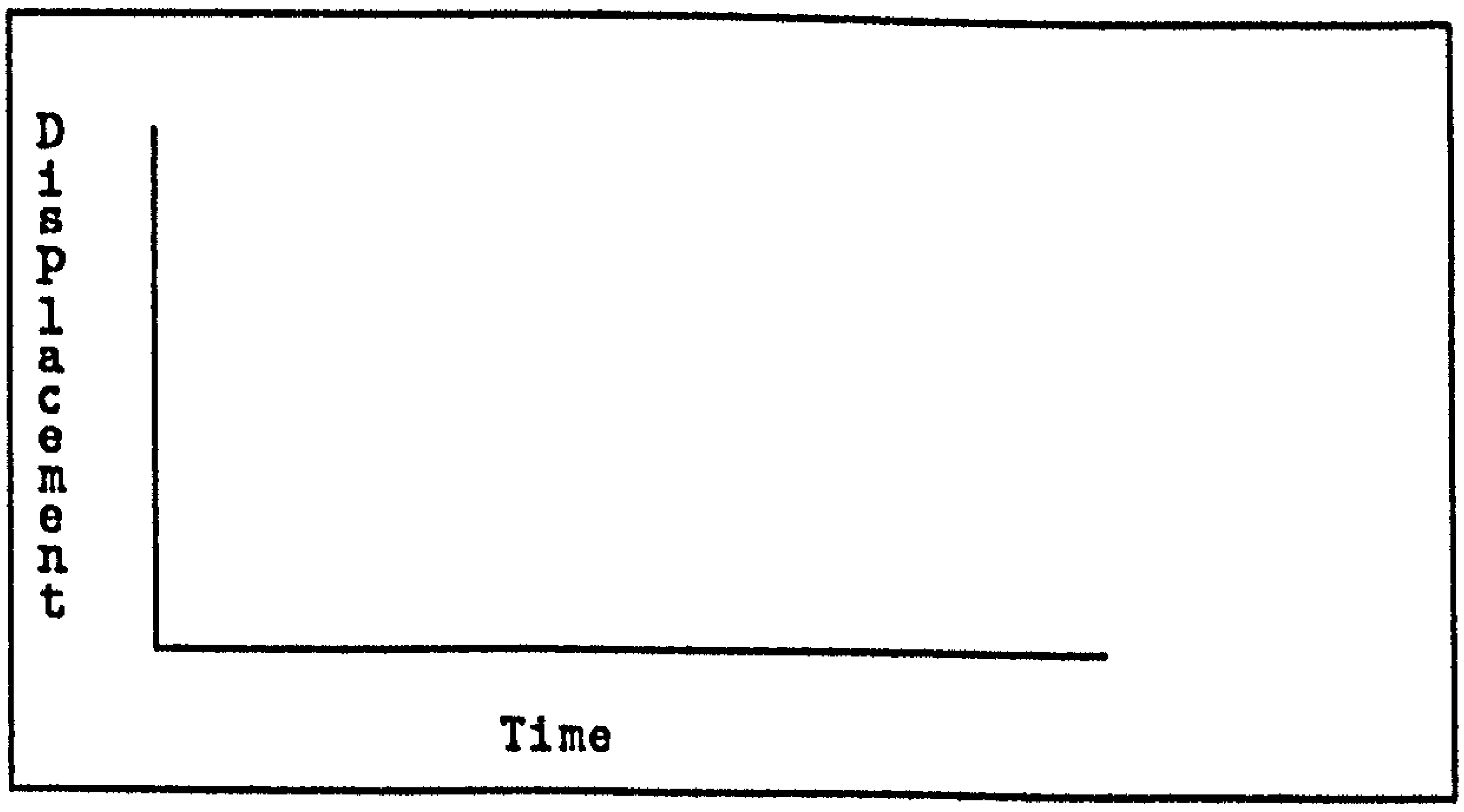


8 A ball moves from A along a smooth table and hits a vertical wall at B. The ball bounces back along the way it came.

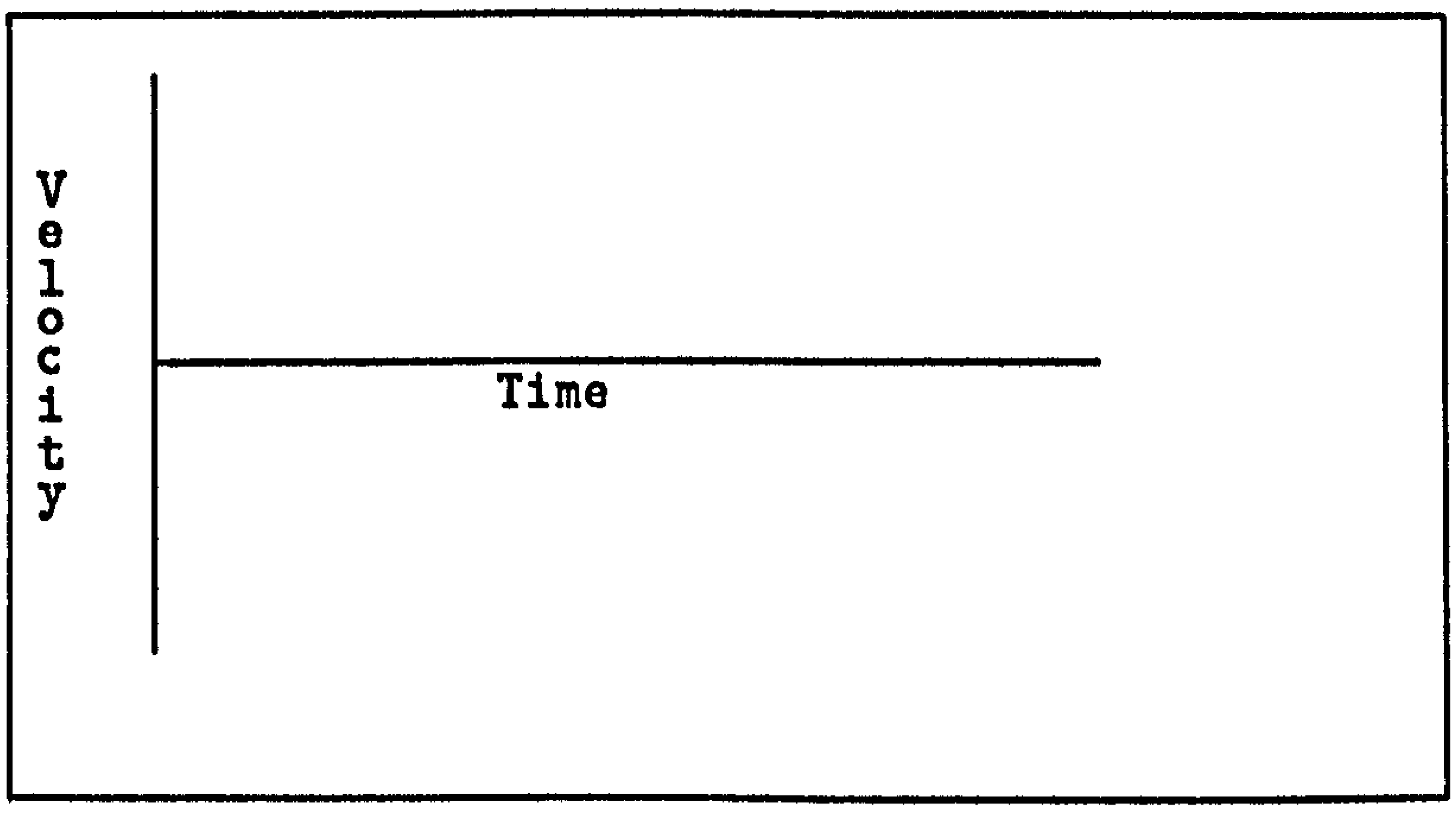


Sketch

a) The displacement-time graph



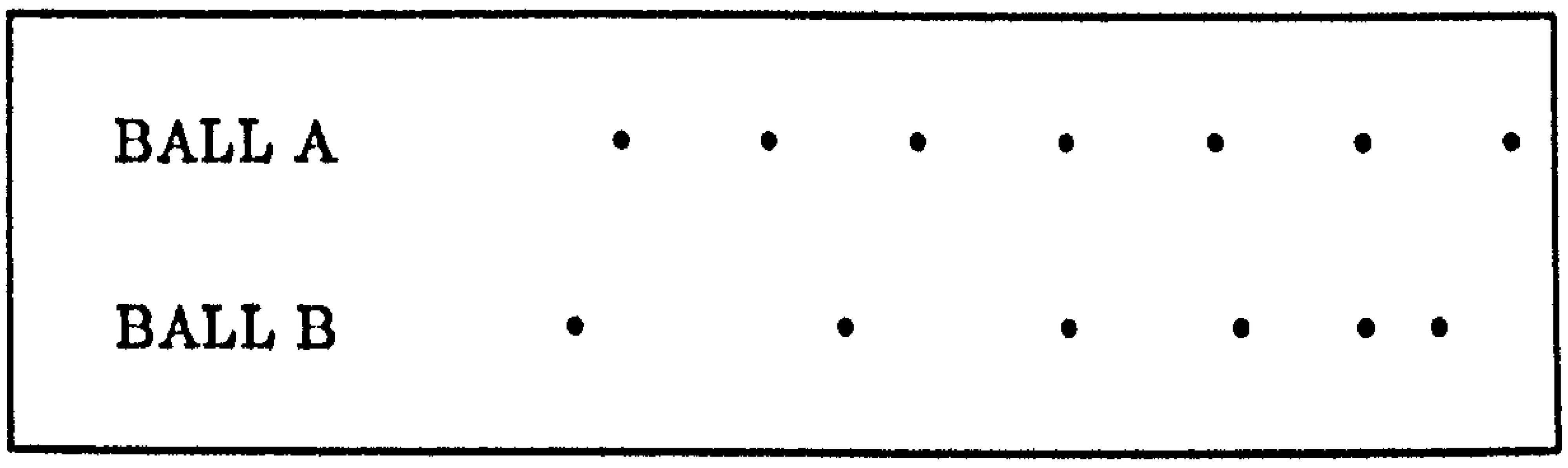
b) The velocity-time graph



9 Ball A rolls along the ground at a steady speed while ball B rolls up a plank.

The following diagram indicates the result of a series of strobe pictures taken from above.

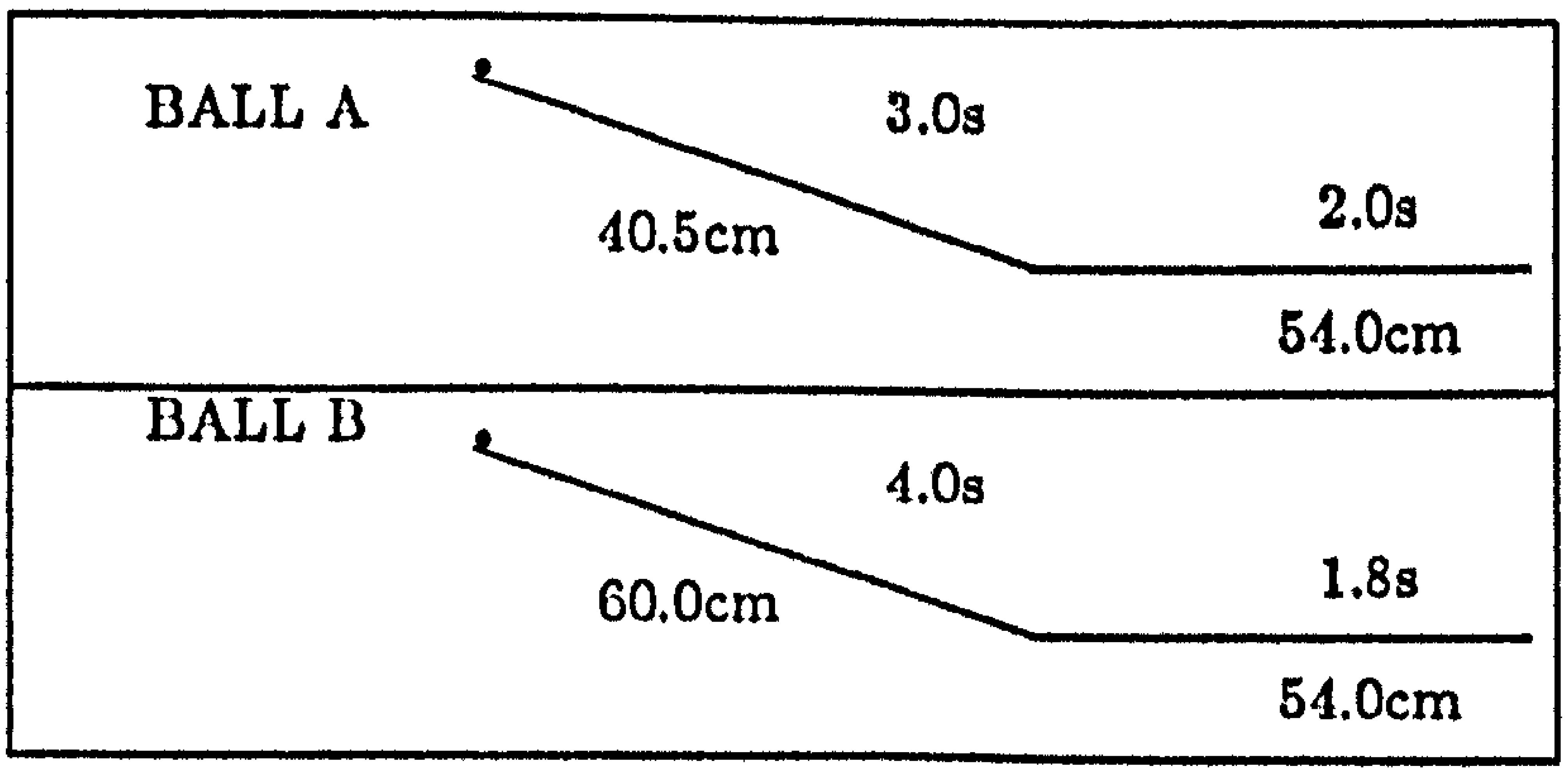
On the diagram, indicate where you think the balls have the same velocity.



10 Two balls rolled down sloping sections of track (not necessarily the same slope) and onto level sections where they have uniform motion.

Times and distances are measured and shown on the diagram.

Answer the following question showing all your working. NO credit will be given for answers which use the formula $s = ut + 1/2at^2$.



Which ball had the greater acceleration?

Appendix E

Sample Worksheets for DYNLAB

The following is a selection of four of the worksheets used with DYNLAB.

About twenty-two worksheets were written of which only six of the sheets were used.

Intro:One	Intro:Two	Intro:Six
Kicks:Start	Kicks:Five	Forces:Four

This usage occurred in the period before asking students to model some of the situations that appeared in the misconception test.

The selection of worksheets reflects the four basic types of worksheet are represented. There is one from each of the sets named INTRO, KICK, FORCE and PROJECT.

DYNLAB WORKSHEET INTRO:ONE

Task
You will be introduced to the DYNAMICS LABORATORY
Instructions
1. Put in

DISK labeled DYNLAB in Drive 1
DISK labeled DYNLAB -INTRO in Drive 2

2. Switch on

APPLE computer
AXIOM printer

After a while you will see a list of names —these are names of situations for you to explore.

3. Choose
the one named ONE by writing

USE ONE

and then pressing the RETURN key.

The computer takes a little time to set things up.
Eventually, you will see some data on the screen.
This is the dynamics data that you will be using.

4. Basically, there are three things that you can do at this point:

Go back and choose a different situation
Change some of the details
Go on to look at a simulation of the situation

Note that the command HELP can be useful in some situations

5. Write the command

RUN

Remember to press the RETURN key!
Eventually, you will see something happening on the screen

Either
press the ESC key
or
wait for a bit
A message will appear on the screen.

6. Obey the command to press the RETURN key.

We are now back where we were before the command RUN.

We will look at some useful commands that help us investigate situations

7. Enter the following command:

LIST

You will see the physics data base on the screen —you may need to press RETURN occasionally to see all of it.

We have a MAP with the statement:

DISPLACEMENT (FROM) FRED (TO) BILL
(OF) 10M (IN DIRECTION) 90

This means that BILL is 10 metres from FRED on a bearing of 90 degrees.

The words in brackets have been added by the program.

We have a JOURNEY BALL which is some information about the journey that the BALL is to take.

START (AT) FRED
VELOCITY (AT) FRED
(OF) 2M/S (IN DIRECTION) 90

This means that the BALL starts at FRED and the BALL's velocity at FRED is 2 metres per second on a bearing of 90 degrees.

From this you can imagine FRED throwing the BALL directly at BILL.

We have a FORCE NIL which usually contains information about what is "pushing" any object.

The statement

GRAVITY OFF

means that there is no constant force due to gravity present.
8. Now write

END

to go back and choose another situation.

RECAP

We have met the following:

USE ...	To use a particular situation
RUN	To see what happens
LIST	To see the physics database
END	To go back and choose a different situation

You have also met the following statements in the database:

MAP

DISPLACEMENT

from place1 to place2 is a distance in metres on a bearing in degrees

JOURNEY

of some body

START

at some place

VELOCITY

at place1 the body has a speed in metres per second on a bearing in degrees

FORCE

with some name

GRAVITY

is either off or on

DYNLAB WORKSHEET KICKS:START

Task

Your task is to find out about angles by describing the direction that a moving body takes.

Instructions

1. Put in

    DISK labeled DYNLAB in Drive 1
    DISK labeled DYNLAB -KICKS in Drive 2

Then switch on

    APPLE computer
    AXIOM printer

After a while you will see a list of names.

2. Choose the one named START by writing

    USE START

Remember to press the RETURN key.
You will see some data on the screen for a little while.
This is the dynamics data that you will be using.

3. Now write

    RUN

Then you will see two places marked on the screen and a flashing object sitting at the lower place.
Either
    Press the ESC key
or
    Wait for a bit
A message will appear on the screen.

4. Obey the command to press the RETURN key.

You are now asked for a command to change the data or the display.

5. Enter the following command:

+ BALL VELOCITY A 10M/S 0

We have to specify that it is the BALL's velocity that is to be altered.
The + means you are adding something to what the program already knows.
Since the BALL starts at A this gives it a velocity at A of 10M/S in the direction 0.

6. Now enter the command RUN and write down the direction.
The BALL goes ____________________________________

7. After you press RETURN, change the velocity at A by typing

+ BALL VELOCITY A 10M/S 90

8. Enter the command RUN and write down the direction.
The BALL goes ____________________________________

9. Repeat for two more cases
a)

+ BALL VELOCITY A 10M/S 180

The BALL goes ____________________________________

b)

+ BALL VELOCITY A 10M/S 270

The BALL goes ____________________________________

10.Hand in your worksheet.

DYNLAB WORKSHEET FORCES:FOUR

Task

You are to experiment with a body sitting on a table and to hand in some results.

Instructions

1. Start the program in the usual way with data disk FORCES and write

    USE FOUR

2. Write:

    RUN

    and you will see three places marked on the screen and a body at rest at B.

3. Write the following and RUN.

    GRAVITY ON

    If you think of ABC as the surface of a horizontal table, the BALL sinks through it!
    You are going to try and get "the table" to stop the BALL sinking through it.

4. Write the command:

    + TABLE FORCE ONE 4N 0

    We are going to see if "the table" can stop the BALL by pushing up on it.

5. By entering commands like the one above and RUNning, fill in the table:

FORCE in N magnitude	VELOCITY in M/S after 1 second	
	magnitude	direction
4		
8		
12		
16		
20		
24		

Remember you can use the command
WRITE
to look at the data collected during the RUN phase.
There is nothing special about choosing to look at the velocity after 1 second.

6. Now try to find the exact magnitude of the force required and answer the following:
The magnitude of the force that keeps the BALL stationary on the table is ---------N

7. Reset the mass of the BALL by

+ BALL MASS 2KG

and basically repeat the above

8. By entering commands like the one above and RUNning, fill in the table:

FORCE in N magnitude	VELOCITY in M/S after 1 second	
	magnitude	direction
4		
8		
12		
16		
20		
24		

9. Now try to find the exact magnitude of the force required and answer the following:

The magnitude of the force that keeps the BALL stationary on the table is --------N

10.Answer the following:

As the mass of the BALL gets larger, "the table" pushes up on the BALL

11.Hand in your worksheet.

DYNLAB WORKSHEET PROJECT:ONE

Task

You are to move a body from rest in one position to rest in another position and to hand in your solution.

Instructions

1. Start up with data disk PROJECT and, if FIRST exists, write:

DESTROY FIRST

2. Then write:

BUILD FIRST

You are to make your own MAP, JOURNEY and FORCE for a BALL that starts at A and ends at B.

First you have to make a MAP.

3. Write

MAKE MAP ONE

There is nothing special about ONE —it is the name of the MAP
Now to define the displacement from A to B.

4. Write a command of the form:

DISPLACEMENT A B ?M 0

Note that there is no need here for a +
You can choose your own magnitude

5. Write

END

To complete the MAP
Now to make the JOURNEY for a BALL

6. Write

MAKE JOURNEY BALL

You have to say where the BALL starts and with what velocity

7. Write

START A

VELOCITY A 0M/S 0

Now to finish the JOURNEY

8. Write

END

Now to make the FORCE which we shall name as DRIVER

9. Write

MAKE FORCE DRIVER

You need to say what the force DRIVER acts on, what kick to give the BALL at the start and what kick to give the BALL at the end.

10. Write

ACTS BALL

KICK ONE A ?NS 0

KICK TWO B ?NS ?

You can give the BALL an initial kick of your own choice.
You will have to make your own decision about KICK TWO's magnitude and direction.
Now to finish the FORCE

11. Write

END

12. To see what you have:

CATALOG

Note that all the files are marked as PASSIVE when they must be ACTIVE.

13. Write

PICKUP MAP ONE

PICKUP JOURNEY BALL

PICKUP FORCE DRIVER

Use CATALOG to see if these files are now ACTIVE.
Otherwise we are ready to USE the situation.

14. Write

END

To finish making the situation named FIRST

15. Now write

USE FIRST

You should see the dynamics data on the screen

16. Write

RUN

You should see a body start at A and stop at B

17. If your KICK did not work then change it by a command like

+ DRIVER KICK TWO B ?NS ?

This will cause your previous entry to be removed since you are redefining your KICK named TWO.

18.Repeat until your KICK works and then write the command

HARDCOPY

The database and information gathered during the RUN phase will be printed out for you.

19.Tear this piece of paper from the axiom and hand it in together with this worksheet.

Appendix F

Construction Worksheets for DYNLAB

The following is a the set of five worksheets used with DYNLAB during the construction phase. They were used in the order:

ONE	EIGHT	THREE	SEVEN	FIVE

but they are in numerical order here.

DYNLAB TEST:ONE

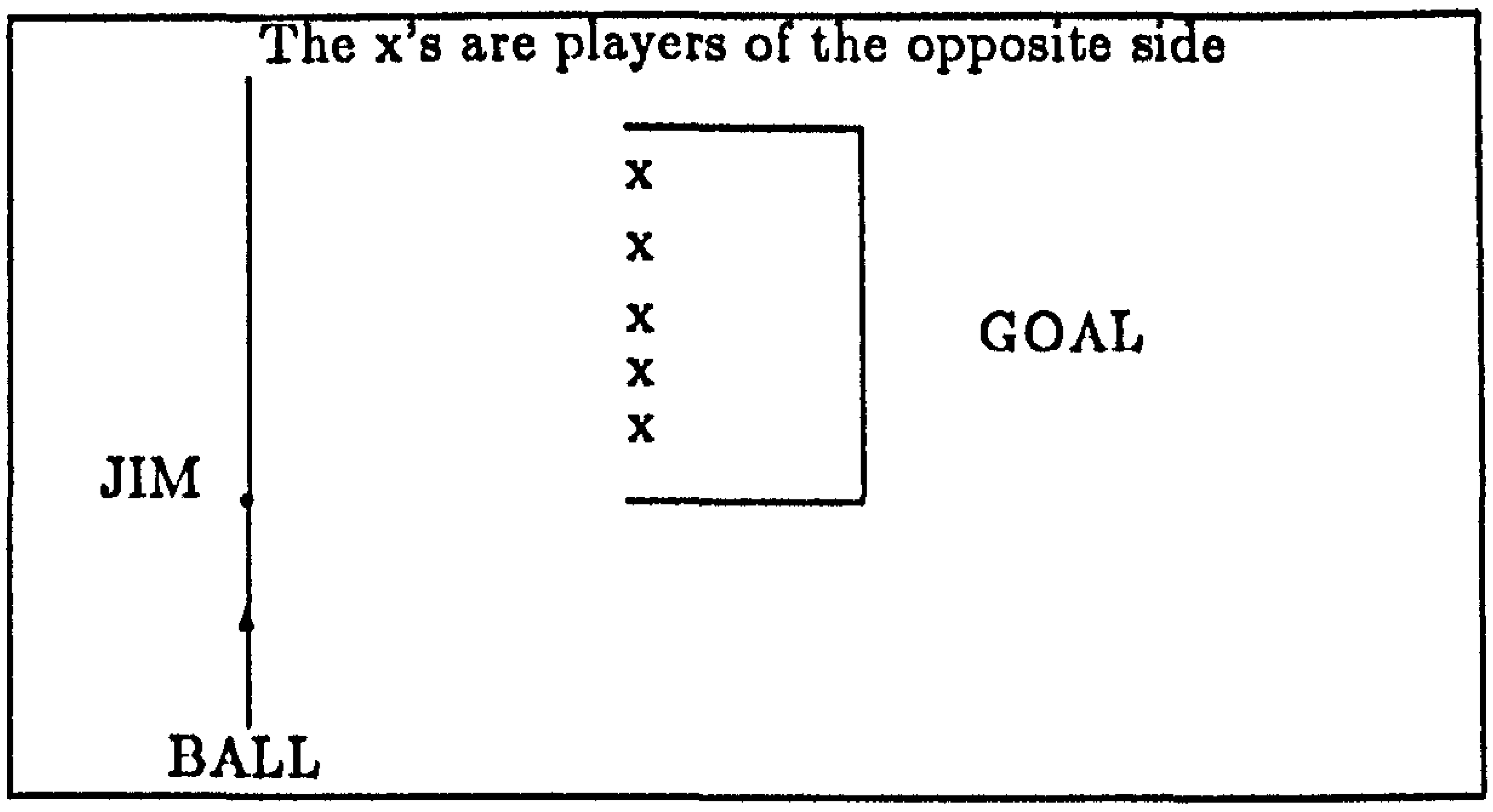
Task

You are to BUILD a situation called ONE that simulates question 1 in the test and hand in your results.

The Question

Jim is playing football when he receives a fast pass straight across the goal mouth. He wants to hit the ball into the gap at the bottom of the goal.

On the diagram, indicate roughly the direction in which he should strike the ball.



Instructions

1. Start up the program as usual with data disk TEST and, if ONE exists, write:

DESTROY ONE

To remove someone else's attempt

2. Now write:

BUILD ONE

It will be up to you to do most of the BUILDing.

3. Write

MAKE MAP ONE

You want the body to start from the place, A, where the pass came from and travel to JIM.
Define a suitable DISPLACEMENT for this.
If you want to add a pictorial representation of the goal you can do so by defining a displacement from JIM to his target, and with 1 additional DISPLACEMENT and JOIN.
Remember to write END and then PICKUP MAP ONE.

4. When you have finished with the MAP, write

MAKE JOURNEY BALL

The BALL is to start at A.
Give the BALL an initial velocity in the direction of JIM —it is up to you to decide how large.
You can give the BALL a reasonable MASS.
Remember to write END and then PICKUP JOURNEY BALL.

5. When you have finished with the JOURNEY, write:

MAKE FORCE SHOT

The FORCE must act on the BALL
You need a KICK called HARD (say)
You will need a command like
KICK HARD JIM ?NS ?
You have to choose all the numbers represented by question marks.
Remember to write END and PICKUP FORCE SHOT.

6. When you have finished with the FORCE, activate the MAP, JOURNEY and the FORCE and write:

END

followed by:

USE ONE

7. Now,

RUN

8. If the BALL does not do as it was meant to do, you can change some of the details. For instance, to change the FORCE, write commands of the form:

+ SHOT FORCE HARD ?N ?

Keep on trying until you are successful.

9. You MUST now write

HARDCOPY

and hand in your printout with your name upon it.

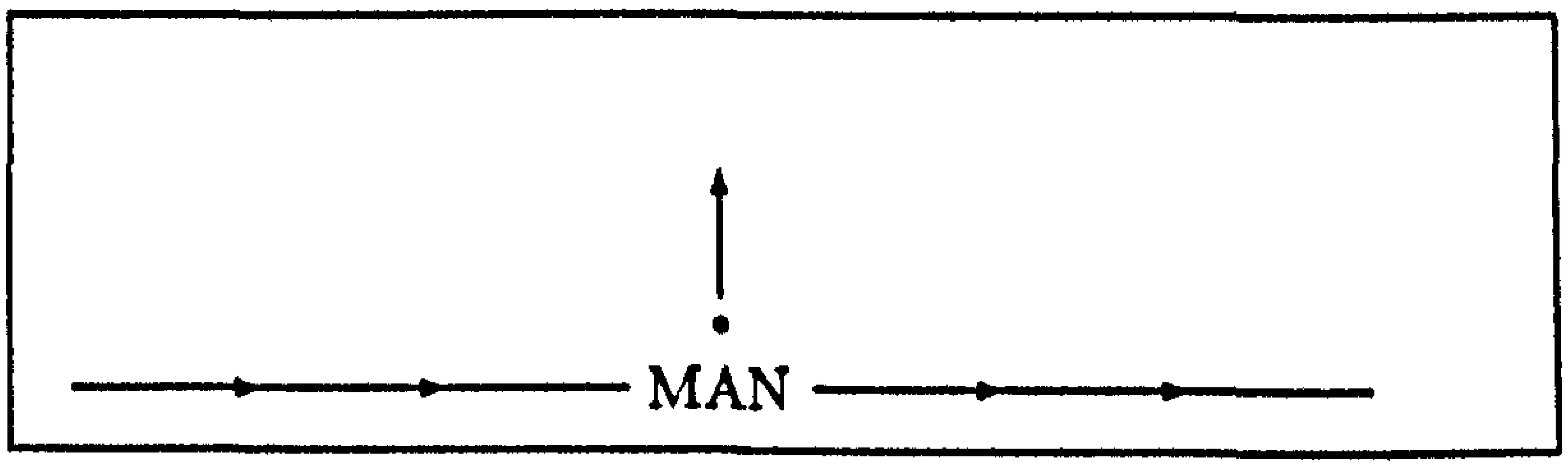
DYNLAB TEST:THREE

Task

You are to BUILD a situation called THREE that simulates question 3 in the test and hand in your results.

The Question

A man stands on a moving walkway and throws a ball vertically into the air.



Indicate which of the following happens:

1. The ball falls behind the man
2. The ball comes back to the man
3. The ball lands in front of the man

Instructions

1. Start up the program as usual with data disk TEST and, if THREE exists, write:

DESTROY THREE

To remove someone else's attempt

2. Now write:

BUILD THREE

It will be up to you to do most of the BUILDing.

3.Write

MAKE MAP ONE

You want the bodies to both to start from some place,A, and the MAN to continue to B, say.
Define a suitable DISPLACEMENT for this.
If you want to represent the walkway, a JOIN might be reasonable.
Remember to write END and then PICKUP MAP ONE.

4. When you have finished with the MAP, write

MAKE JOURNEY BALL

The BALL is to start at A.
Give the BALL an initial velocity —but remember that we are going to KICK it into the air and that the BALL is in the MAN's hand.
You can give the BALL a reasonable MASS if you wish.
Remember to write END and then PICKUP JOURNEY BALL.

5. When you have finished with JOURNEY BALL, write

MAKE JOURNEY MAN

The MAN is to start at A and travel to B.
Give the MAN an initial velocity.
Remember to write END and then PICKUP JOURNEY MAN.

6. When you have finished with the JOURNEY, write:

MAKE FORCE THROW

The FORCE must act on the BALL.
You need a KICK called UP (say)
You will need a command like
    KICK UP A ?NS ?
You have to choose all the numbers represented by question marks.
You also need a FORCE with label GRAV to simulate the effect of gravity acting on the BALL of the form:
    FORCE GRAV ?N ?
It would be better to switch on GRAVITY since it is unfair to think of gravity acting only on the BALL!!! but if you try it that way you will have an interesting problem to solve.
Remember to write END and PICKUP FORCE THROW.

7. When you have finished with the FORCE, activate the MAP, the two JOURNEYs and the FORCE and write:

END

followed by:

USE THREE

8. Now,

RUN

9. If the BALL does not do as it was meant to do, you can change some of the details. For instance, to change the part of the FORCE simulating the throw, write commands of the form:

+ THROW KICK UP A ?NS ?

Keep on trying until you are successful. Can you see the answer to the original question?

10. You MUST now write

HARDCOPY

and hand in your printout with your name upon it.

DYNLAB TEST:FIVE

Task
You are to BUILD a situation called FIVE that simulates question 5 in the test and hand in your results.
The Question

A rocket is moving sideways in deep space, with its engines off, from point A to point B.

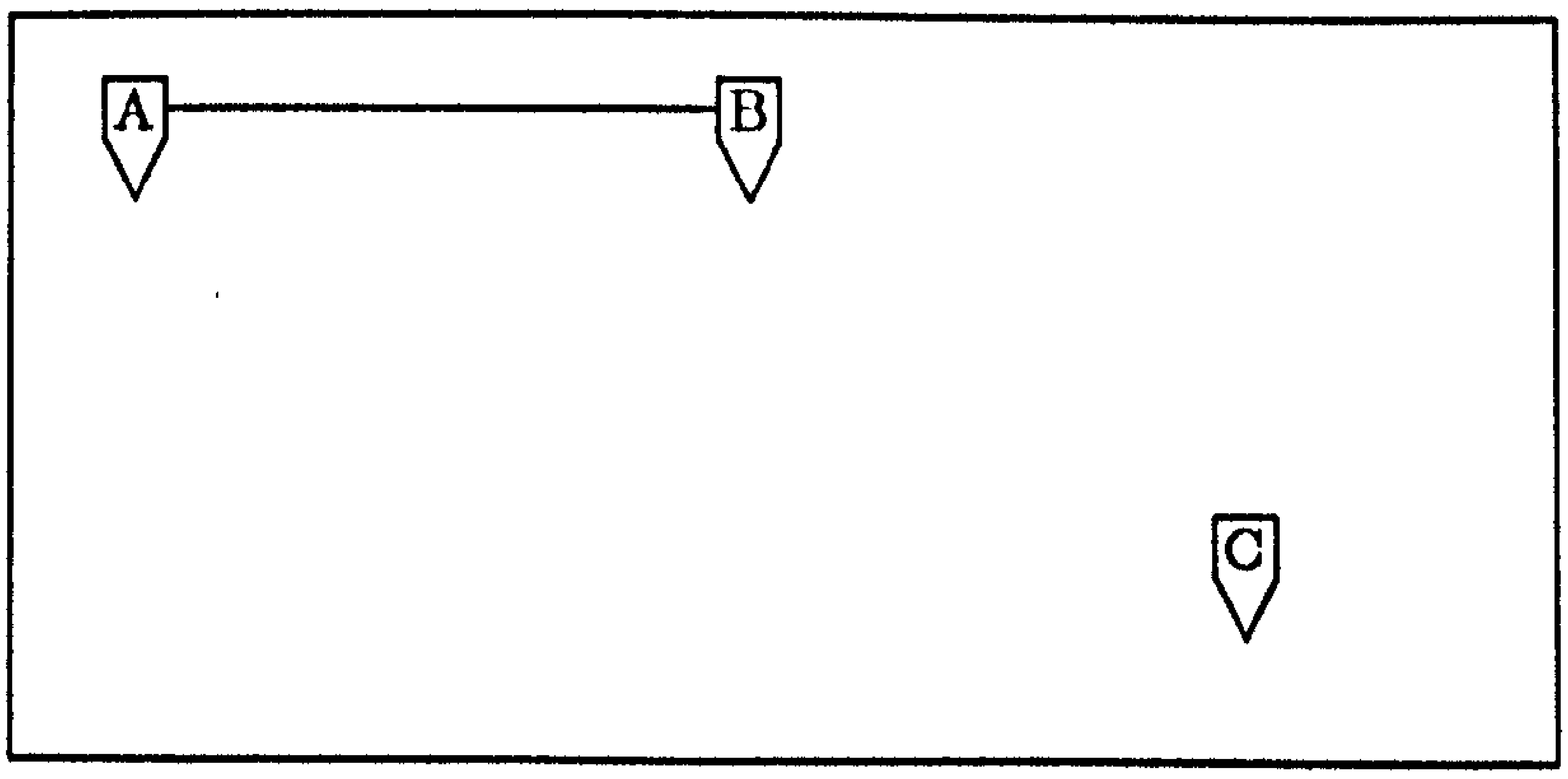
It is not near any planets or other outside forces.

Its engine is fired at point B and left on for 2 seconds while the rocket travels from B to C.

On the diagram, draw in the shape of the path

a) from B to C

b) from C —remember that the engine is turned off now.



Instructions
1. Start up the program as usual with data disk TEST and, if FIVE exists, write:

DESTROY FIVE

To remove someone else's attempt

2. Now write:

BUILD FIVE

It will be up to you to do most of the BUILDing.

3. Write

MAKE MAP FIVE

You want the body to start from the place, A, where the rocket appears and travel to B.
Define a suitable DISPLACEMENT for this.
If you wish to do so, select a DISPLACEMENT to define the position of B.
Remember to write END and then PICKUP MAP ONE.

4. When you have finished with the MAP, write

MAKE JOURNEY ROCKET

The ROCKET is to appear on the screen at A.
Give the ROCKET an initial velocity in the direction of B —it is up to you to decide how large.
You can give the ROCKET a reasonable MASS.
Remember to write END and then PICKUP JOURNEY BALL.

5. When you have finished with the JOURNEY, write:

MAKE FORCE FIRE

The FORCE must act on the ROCKET.
You will need two FORCE's: the first called WAIT (say) and the second called PUSH.
WAIT must be arranged to cease when the ROCKET gets to B. You will need a command like

FIRE FORCE WAIT ?N ? ....

The ..... indicates a condition equivalent to "until the (TIME, DISPLACEMENT or VELOCITY) is such and such".
You have to choose the condition.
You also have to choose all the numbers represented by question marks.
Now for the second force PUSH. You will need a command like:

FIRE FORCE PUSH ?N ? ....

The ..... indicates a condition equivalent to "until the INCREASE in (TIME, DISPLACEMENT or VELOCITY) is such and such".
Remember to write END and PICKUP FORCE TABLE.

6. When you have finished with the FORCE, activate the MAP, JOURNEY and the FORCE and write:

END

followed by:

USE FIVE

7. Now,

RUN

8. If the ROCKET does not do as it was meant to do, you can change some of the details. For instance, to change one of the FORCEs, write commands of the form:

+ FIRE FORCE PUSH ?N ? ......

Where the dots stand for a condition similar to

DISPLACEMENT ?M

Keep on trying until you are successful.
Now you can see what path the ROCKET takes!

9. You MUST now write

HARDCOPY

and hand in your printout with your name upon it.

DYNLAB TEST:SEVEN

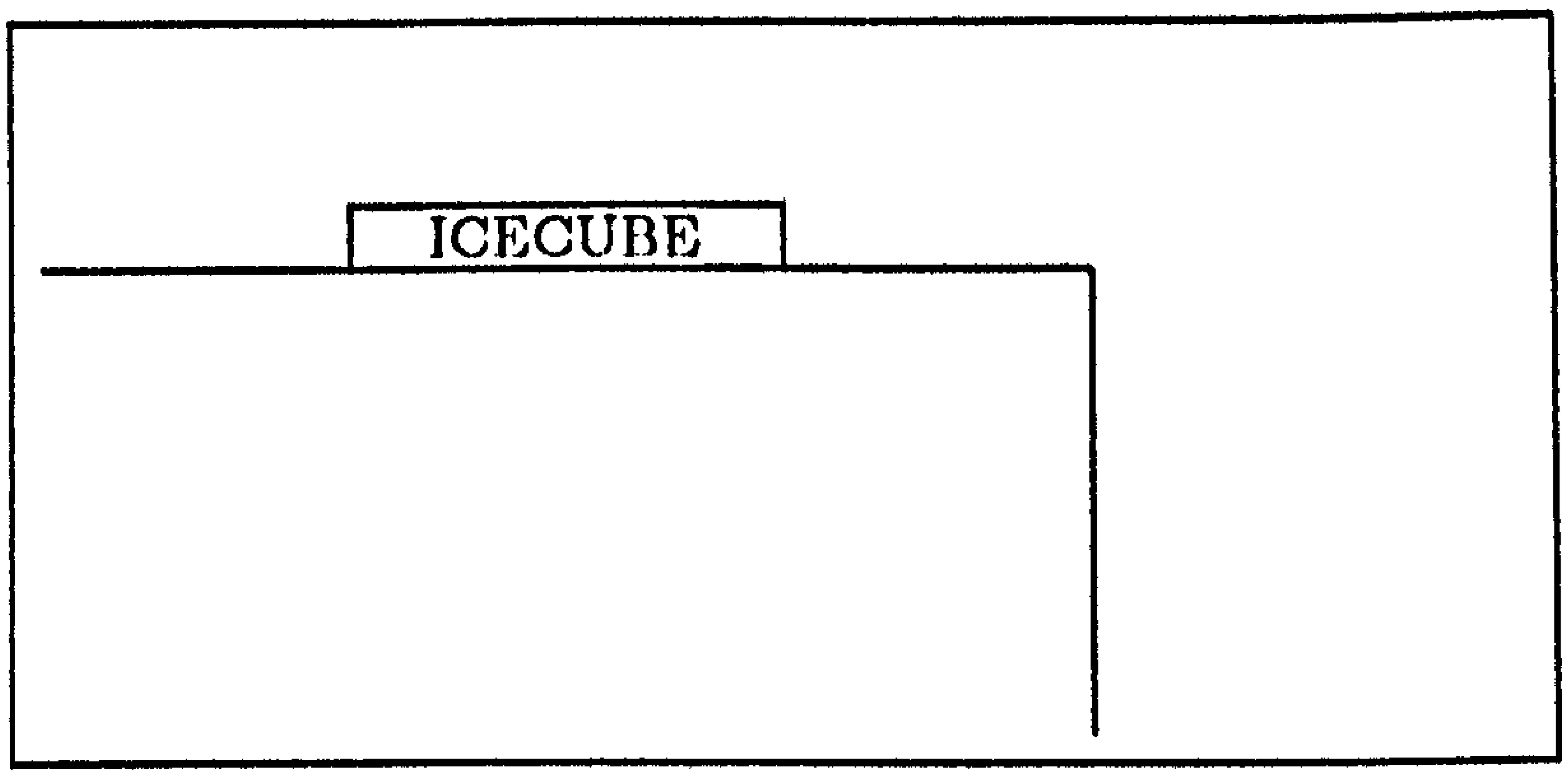
Task

You are to BUILD a situation called SEVEN that simulates question 7 in the test and hand in your results.

The Question

An ice cube slides along a smooth table and falls off the end moving fast.

On the diagram, indicate the path that the cube takes.



Instructions

1. Start up the program as usual with data disk TEST and, if SEVEN exists, write:

DESTROY SEVEN

To remove someone else's attempt

2. Now write:

BUILD SEVEN

It will be up to you to do most of the BUILDing.

3. Write

MAKE MAP ONE

You want the body to start from some place, A, and travel to B, the edge of the table.
Define a suitable DISPLACEMENT for this.
If you want to add a pictorial representation of the table, you can do so by JOINing A and B and with 1 additional DISPLACEMENT and JOIN.
Remember to write END and then PICKUP MAP ONE.

4. When you have finished with the MAP, write

MAKE JOURNEY CUBE

The CUBE is to start at A.
Give the CUBE an initial velocity in the direction of B —it is up to you to decide how large.
Remember to write END and then PICKUP JOURNEY CUBE.

5. When you have finished with the JOURNEY, write:

MAKE FORCE TABLE

The FORCE must act on the CUBE
You need a force called PUSH (say)
Choose ONE as the label for the FORCE
The difficult bit is to turn the PUSH off at B
You will need a command like
FORCE ONE ?N ? DISPLACEMENT ?N
Note the extra condition which means that the force is such and such until the magnitude of the displacement moved by the CUBE is whatever.
You have to choose all the numbers represented by question marks.
Remember to write END and PICKUP FORCE TABLE.
Note that you will need to add GRAVITY when you are USEing the situation.

6. When you have finished with the FORCE, activate the MAP, JOURNEY and the FORCE and write:

END

followed by:

USE SEVEN

7. Now, turn on GRAVITY and

RUN

8. If the CUBE does not do as it was meant to do, you can change some of the details. For instance, to change the FORCE, write commands of the form:

\+ PUSH FORCE ONE ?NS ? DISPLACEMENT ?N

Keep on trying until you are successful.
Now you can see what path the cube takes!

9. You MUST now write

HARDCOPY

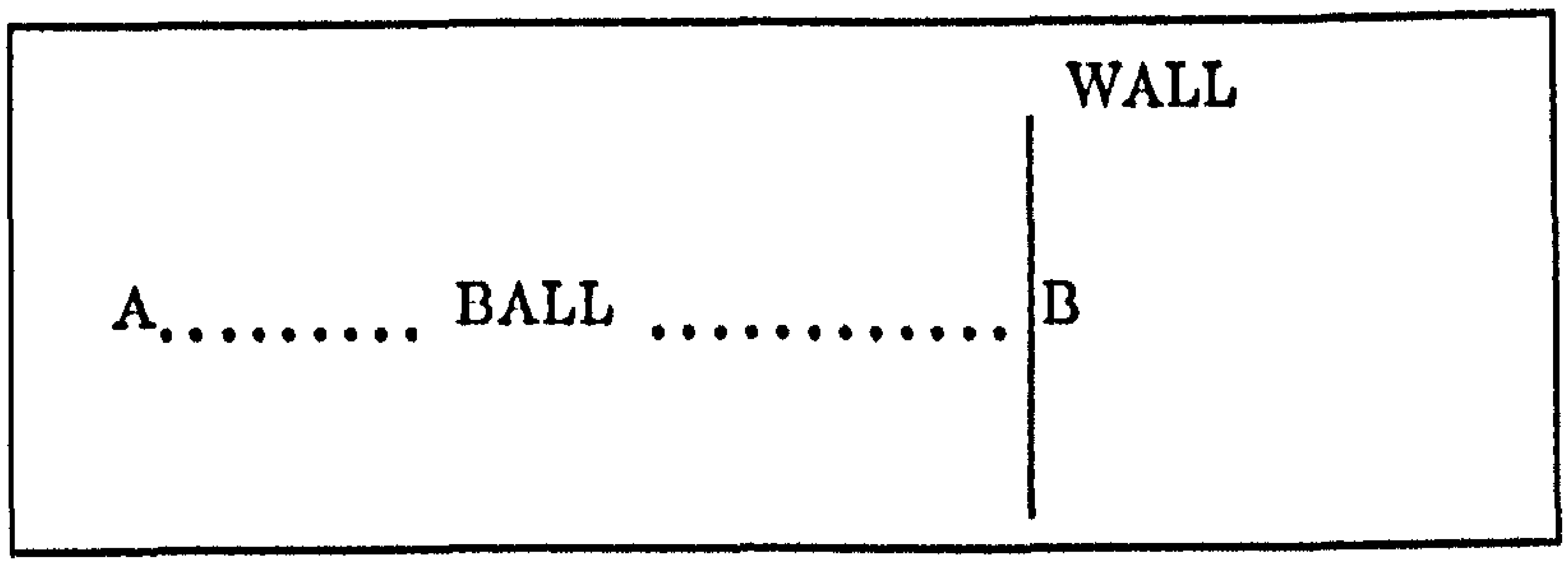
and hand in your printout with your name upon it.

DYNLAB TEST:EIGHT

<u>Task</u>
You are to BUILD a situation called EIGHT that simulates question 8 in the test and hand in your results.
<u>The Question</u>

A ball moves from A along a smooth table and hits a vertical wall at B.

The ball bounces back along the way it came.



Sketch
a) The displacement-time graph
b) The velocity-time graph

<u>Instructions</u>
1. Start up the program as usual with data disk TEST and, if EIGHT exists, write:

DESTROY EIGHT

To remove someone else's attempt

2. Now write:

BUILD EIGHT

It will be up to you to do most of the BUILDing.

3.Write

MAKE MAP ONE

You want the body to start from A and travel to B. Define a suitable DISPLACEMENT for this.
If you want to add a pictorial representation of the wall, you can do so with 1 or 2 DISPLACEMENTS and a JOIN.
Remember to write END and then PICKUP MAP ONE.

4. When you have finished with the MAP, write

MAKE JOURNEY BALL

The BALL is to start at A.
Give the BALL an initial velocity in the direction of B —it is up to you to decide how large.
Remember to write END and then PICKUP JOURNEY BALL.

5. When you have finished with the JOURNEY, write:

MAKE FORCE BOUNCE

The FORCE must act on the BALL
There must be a single KICK at B —you must decide how much and in what direction.
Choose ONE as the label for the KICK.
The BALL must go back from B to A.
Remember to write END and PICKUP FORCE BOUNCE.

6. When you have finished with the FORCE, activate the MAP, JOURNEY and the FORCE and write:

END

followed by:

USE EIGHT

7. Now

RUN

8. If the BALL does not do as it was meant to do, you can change some of the details. For instance, to change the KICK, write commands of the form:

+ BOUNCE KICK ONE B ?NS ?

Keep on trying until you are successful.

9. Now you can investigate the velocity-time graph with the command:

USE GRAPH

The graph is set up to be that of the magnitude of the velocity of the BALL against time.
So you do not get negative y coordinates!

and

RUN

If you want to sketch the traditional velocity-time graph, you will need to think what happens when the BALL hits the WALL.

10.Now to investigate the displacement-time graph with:

GRAPH BALL DISPLACEMENT TIME

and

RUN

11.You MUST now write

HARDCOPY

and hand in your printout with your name upon it.

Appendix G

Summary of DYNLAB Commands

G.1 Situation Filer

In the following, <name> and <new name> are the names of situations —up to 6 alphanumeric characters long.

Handling Whole Situations		
USE	<name>	
DESTROY	<name>	
EDIT	<name>	
BUILD	<name>	
RENAME	<name>	<new name>

G.2 Situation Editor

Handling Parts of Situations			
MAKE	<file>	<name>	
CHANGE	<file>	<name>	
DESTROY	<file>	<name>	
LIST	<file>	<name>	
PICKUP	<file>	<name>	
PUTBACK	<file>	<name>	
COPY	<file>	<name>	<newname>
RENAME	<file>	<name>	<newname>
CATALOG			
HELP			
END			

where

<file>	is one of MAP, JOURNEY or FORCE
<name>	is a name up to 6 alphanumeric characters long
<newname>	is a name up to 6 alphanumeric characters long

Adding Facts to the MAP file				
DISPLACEMENT	<place>	<place>	<mag_d>	<direction>
JOIN	<place>	<place>		

Adding Facts to the JOURNEY file			
START	<place>		
MASS	<mag_m>		
VELOCITY	<place>	<mag_v>	<direction>

Adding Facts to the FORCE file				
ACTS	<object>			
KICK	<label>	<place>	<mag_k>	<direction>
FORCE	<label>	<mag_f>	<direction>	
FORCE	<label>	<mag_f>	<direction>	<extrabit>

where <extrabit> is one of

<variable>	<mag_units>	
INCREASE	<variable>	<mag_units>
DECREASE	<variable>	<mag_units>

and

<variable>	is one of DISPLACEMENT, VELOCITY, TIME
<mag_units>	is a real number followed by the relevant units
<place>	is a location on the screen up to 6 alphanumeric characters long
<object>	is the name of a JOURNEY file
<fname>	is the name of a FORCE file
<label>	is an identifier up to 6 alphanumeric characters long
<direction>	is an angle —no units
<mag_d>	is the size of the displacement in M
<mag_v>	is the size of the velocity in M/S
<mag_m>	is the size of the mass in KG
<mag_k>	is the size of the impulse in NS
<mag_f>	is the size of the force in N
<mag_t>	is the size of the time in S

Note that there is a fair degree of latitude accepted in entering units. For example KGMS*-1 is equivalent to NS. For that matter, so is M/S/KG*-1.

The major differences between these commands and the "interactive" ones are:

1. A "+" preceding each command is needed

2. The object for the commands START, VELOCITY and MASS must be specified

3. The FORCE must be specified for the commands ACTS, KICK, and FORCE

Removing Data			
REMOVE	DISPLACEMENT	<place>	<place>
REMOVE	JOIN	<place>	<place>
REMOVE	START		
REMOVE	MASS		
REMOVE	VELOCITY	<place>	
REMOVE	KICK	<label>	
REMOVE	FORCE	<label>	
REMOVE	ACTS	<object>	

G.3 Situation Interactor

The additional features provided in addition to the facilities to edit the MAP, JOURNEYs and FORCEs.

Gravity	
GRAVITY	ON
GRAVITY	OFF

Describing the Display		
NOPRINT		
PRINT	<obj>	DISPLACEMENT
PRINT	<obj>	VELOCITY
PRINT	<obj>	ACCELERATION
PRINT	<obj>	AVERAGE VELOCITY
PRINT	<obj>	AVERAGE ACCELERATION
NEWGRAPH		
GRAPH	<obj>	<variable1> <variable2>

where <variable1> and <variable2> are one of DISPLACEMENT, VELOCITY, ACCELERATION, and TIME and <variable1> is not the same as <variable2>.

Changing the Display		
USE	PRINT	
USE	GRAPH	
USE	NOTHING	
SCALE	DISPLACEMENT	<number>
SCALE	VELOCITY	<number>
SCALE	ACCELERATION	<number>
SCALE	TIME	<number>

Note that no units are required here. Also note that a number

- Must be smaller than 100000 and
- Must not lie between 0 and 0.001

Utilities			
TRACKS	ON	TRACKS	OFF
LABELS	ON	LABELS	OFF
TRACE	ON	TRACE	OFF
WRITE		LIST	
STATE		HELP	
HARDCOPY			
RUN		END	

Appendix H

Exam Results of Students using DYNLAB

The 'O' Grade results for the ten S4 students.

Student	Number Grade	Letter Grade
Student A	1	A
Student B	5	A
Student C	1	A
Student D	1	A
Student E	1	A
Student F	1	A
Student G	8	C
Student H	3	A
Student I	2	A
Student J	6	B

Note that Number Grades from 1 to 5 map to Grade A, Number Grades 6 and 7 map to Grade B and Number Grades 8 and 9 to Grade C.

Appendix I

Sample Worksheets for ELAB

The following is a selection of three of the worksheets used with ELAB.

About twenty-six worksheets were written of which all but four sheets were used. There were six introductory sheets:

Intro:One	Intro:Two	Intro:Three
Intro:Four	Intro:Five	Intro:Six

This usage occurred in the period immediately before asking the students to model the situations that appeared in the misconception test.

The three introductory worksheets selected are the first three.

ELAB WORKSHEET INTRO:ONE

1 What the Program Can Do

Create DC and AC circuits
Analyse DC and AC circuits

There are some limitations but these will be outlined later.
You are going to start by analysing DC circuits.
DC stands for DIRECT CURRENT.

2 How to Use the Program

a) To use the ELECTRICITY LABORATORY you will need:

DISK labeled ELAB
DISK labeled ELAB —INTRO
A worksheet with the heading ELECTRICITY LABORATORY

b) Put in

DISK labeled ELAB in Drive 1
DISK labeled ELAB —INTRO in Drive 2

c) Switch on

APPLE computer

After a while you will see:

	COMMAND	CIRCUIT NAME
□	USE	ONE
		TWO
	BUILD	THREE
		FOUR
	DESTROY	FIVE
	RENAME	
	STOP	

The white rectangle opposite USE is called the cursor.
The column headed COMMANDS is the list of valid commands while the one headed CIRCUIT NAME is the list of available circuits.

d) Press

SPACEBAR

You should see the cursor move to BUILD.

Keep pressing

SPACEBAR

until the cursor is opposite USE.

Now press

RETURN

You have chosen to USE a circuit —now you must choose which one. You will choose it in the same way that you chose a command.

You will see:

```
COMMAND          CIRCUIT NAME

USE          □   ONE
                 TWO
BUILD            THREE
                 FOUR
DESTROY          FIVE

RENAME

STOP
```

The cursor is now opposite the circuit named ONE.

e) The circuit you want is named TWO so press

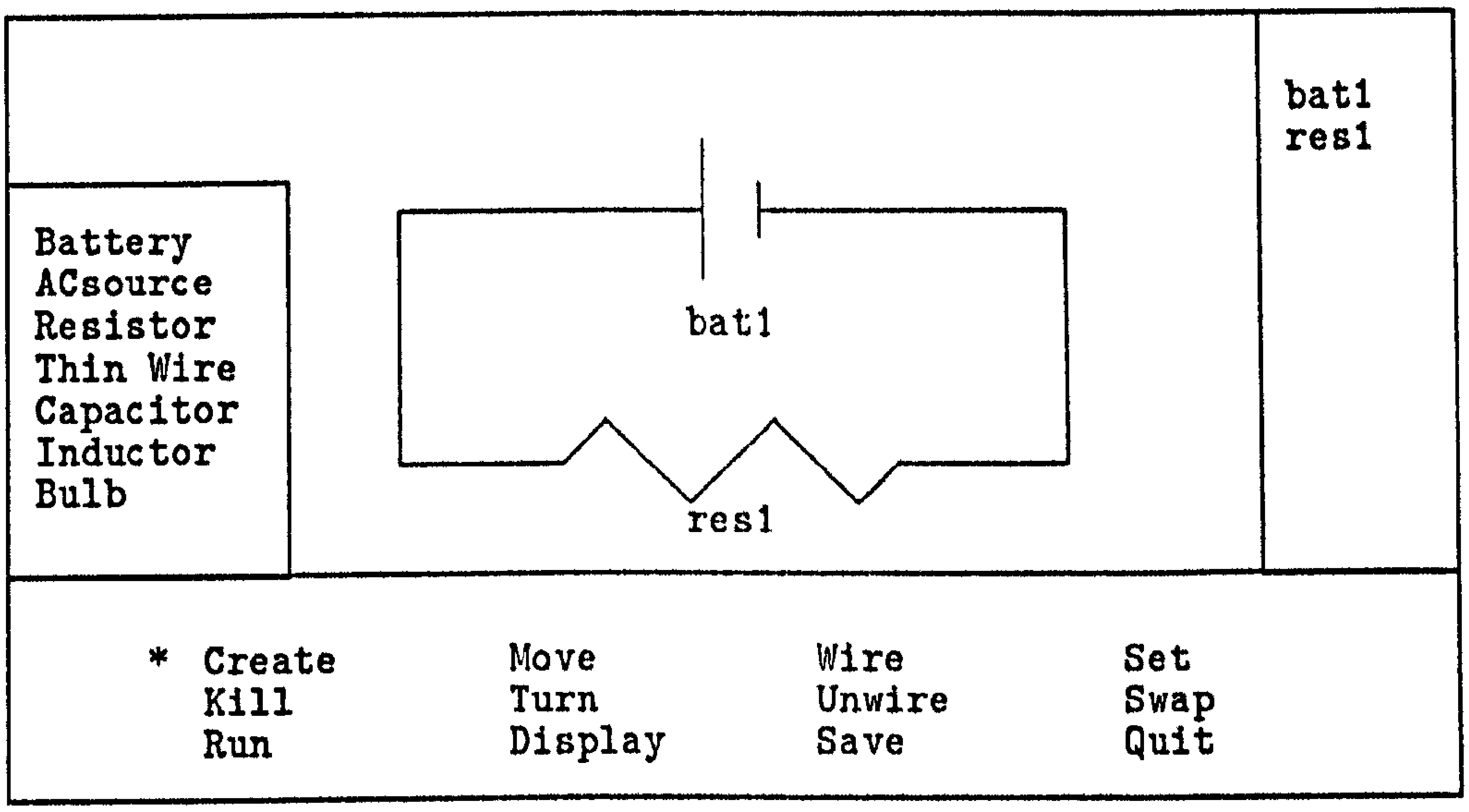
SPACEBAR

to move the cursor next to TWO and press

RETURN

to select the circuit named TWO.

f) Wait a while and the screen looks like:



The left hand side is different. You should see symbols standing for battery, ac-source etc. By comparing the symbols on the screen with the names on the above diagram you should be able to decide what each symbol stands for.

The cursor is opposite the command CREATE.

The commands form a list. Choosing one is just like the way you chose the command 'USE' and the circuit 'TWO'.

g) Now move the cursor to RUN by pressing

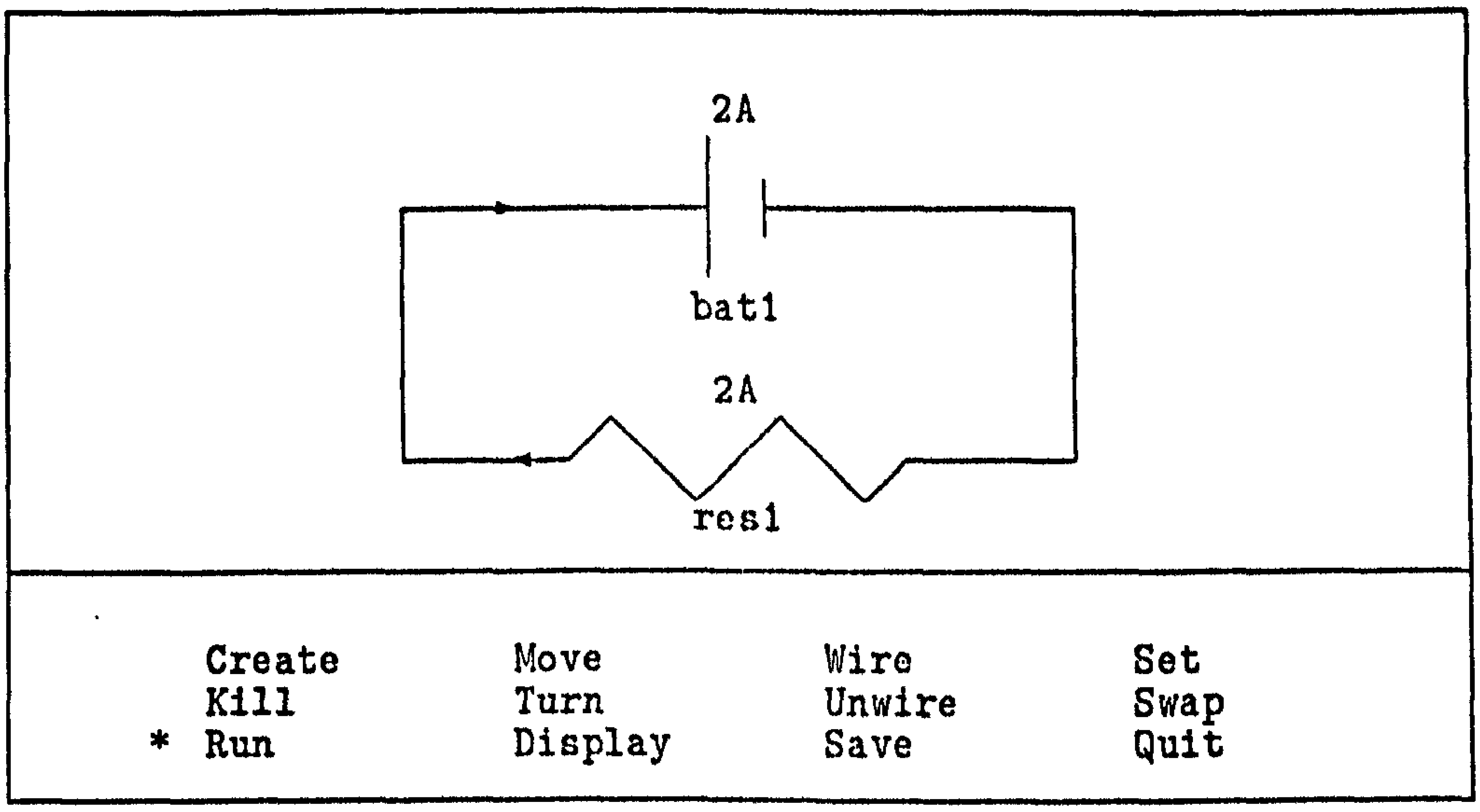
SPACEBAR

eight times until the cursor is opposite RUN.

Now press

RETURN

and the screen becomes:



where each number above an object indicates the current through the object in amps.

> You can tell that the number is in amps because A stands for Amps.
> You can tell the direction of the current from the arrow.

h) To let someone else use the program or to use another circuit, press

SPACEBAR

three times and select QUIT by pressing

RETURN

i) If no one is to follow you, select

STOP

then

Take <u>both</u> disks out
Turn off the APPLE

3 What You Have Learned

How to Move Cursors along lists of things

The meaning of USE: basically, look at or change an already existing circuit

The appearance of a circuit

The symbol for Battery:

The symbol for AC source:	
The symbol for Resistor:	
The symbol for (Resistance) Wire:	
The symbol for Capacitor:	
The symbol for Inductor:	
The symbol for Bulb:	
The meaning of RUN:	basically, show me the current through all the objects on the screen
The meaning of QUIT:	used to choose another circuit or stop
The meaning of STOP:	

ELAB WORKSHEET INTRO:TWO

1 What You Are Going To Do

You are going to see how to change the resistance of a resistor. The same basic method will apply to changing any other value —for example, the EMF of a battery.

a) If the program is not running, start up with

DISK labeled ELAB in Drive 1
DISK labeled ELAB —INTRO in Drive 2

After a while you will see:

	COMMAND	CIRCUIT NAME
□	USE	ONE
		TWO
	BUILD	THREE
		FOUR
	DESTROY	FIVE
	RENAME	
	STOP	

The white rectangle opposite USE is called the cursor.

b) Press

RETURN

to select USE.

From now on, we shall refer to moving the cursor with the SPACEBAR and pressing RETURN as "select".
The cursor is now opposite the circuit named ONE.

c) What do we do if we decide that we don't want to USE any circuit? Press

ESC

and the cursor moves back to USE.

The key marked ESC is a special one. It always has the effect of aborting the current activity.

Select

USE

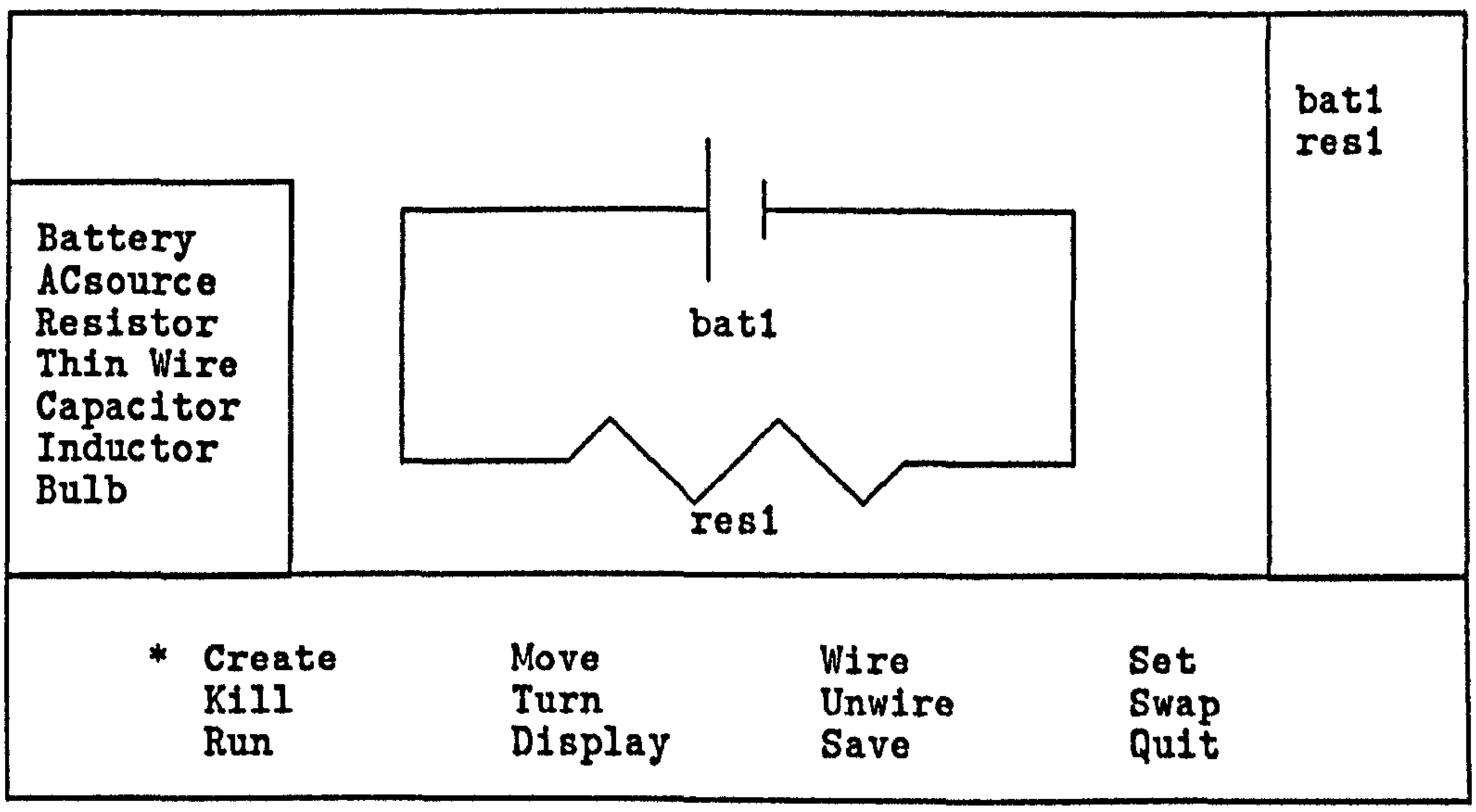
again and the cursor is now opposite the circuit named ONE. Next, press

RETURN

to select ONE.

> Always try pressing the key marked ESC if you want to stop doing something. This usually works well.

d) Wait a while and the screen looks like:



> except you should see symbols standing for battery, acsource etc.
> The cursor is opposite the command CREATE.

2 To Change The Resistance of a Resistor

a) We want to find out the value of the resistance of "res1" and then change it. Select

SET

> You still have to choose "res".
> A new cursor appears at the right hand side of the screen:
> | bat1
> res1
> Select
> res1

The bottom of the screen becomes:

```
        Create       Move        Wire       * Set
        Kill         Turn        Unwire       Swap
        Run          Display     Save         Quit

* resistance 1
```

where the resistance is in Ohms.

b) Opt to change the resistance by selecting

resistance

Since there is only one item in the list pressing the SPACEBAR only appears to have no effect.

The screen becomes:

```
        Create       Move        Wire       * Set
        Kill         Turn        Unwire       Swap
        Run          Display     Save         Quit

resistance *
```

and the program is waiting for you to type in the change (remember that pressing ESC would abort).

Type in

23

Remember to press RETURN to enter the result into the computer.

and the new resistance of "res1" will be 23 Ohms.

c) Select

RUN

Write down the following:

1) The current through "bat1" is __________ Amps

2) The current through "res1" is __________ Amps

e) Select

QUIT

then, if no one is to follow you,

STOP

and

Take both disks out
Turn off the APPLE

3 What You Have Learned

The meaning of SET: to look at and/or change some detail of an object

The use of ESC: to stop doing something

ELAB INTRO:THREE

1 What You Are Going To Do

In the last exercise you analysed a circuit and determined the current through a battery and a resistor.

You are going to find out the potential difference across the same battery and resistor. Further, you will also find the power dissipated by the battery and resistor.

a) Start up with

DISK labeled ELAB in Drive 1
DISK labeled ELAB —INTRO in Drive 2

b) Select

USE

and then select

ONE

c) Wait a while and the screen looks like:

	COMMAND	CIRCUIT NAME
□	USE	ONE
		TWO
	BUILD	THREE
		FOUR
	DESTROY	FIVE
	RENAME	
	STOP	

except you should see symbols standing for battery, acsource etc.
The cursor is opposite the command CREATE.

2 To Examine the Potential Difference Across an Object

We want to examine the current through each object and then the potential difference across each object.

a) Select

RUN

and write down the following:

1) The current through "bat1" is __________ Amps

2) The current through "res1" is ___________ Amps

b) Now select

DISPLAY

and the very bottom of the screen becomes:

```
* current    pd          power        v/i
```

pd stands for POTENTIAL DIFFERENCE.
v/i stands for the experimental value of the potential difference(v) divided (when possible) by the current(i).

Use the cursor to select

pd

Now select

RUN

Note that, in a DC circuit, the POTENTIAL DIFFERENCE is always given as a DROP in the direction of the arrow.

and write down the following:

1) The potential difference across "bat1" is __________ Volts

2) The potential difference across "res1" is ___________ Volts

3 To Examine the Electrical Power Converted by an Object

a) Go through the above again but this time select

power

instead of pd.

Remember to select
RUN
Note that the power is always given as the power converted from electrical energy into some other form.

b) Write down the following:

1) The power dissipated by "bat1" is __________ Watts

2) The power dissipated by "res1" is ___________ Watts

4 To Examine the Experimental Value of V/I for an Object

a) Now select

DISPLAY V/I

and

RUN

b) Write down the following:

1) The value of v/i for "bat1" is ---------- Ohms

2) The value of v/i for "res1" is ----------- Ohms

The value of v/i is often measured in Ohms.

c) Finish in the usual way. That is, select

QUIT

and, if no one is to follow you, select

STOP
Take both disks out
Turn off the APPLE

5 What You Have Learned

The meaning of DISPLAY: which of current, pd, power or v/i will be displayed on the screen whenever RUN is selected

How to choose to output current, p.d., power or "v/i"

Appendix J

Construction Worksheets for ELAB

The following is a set of the first three worksheets used with ELAB during the construction phase. They were used in their numeric order.

ELAB QUESTION:ONE

A What You Are Going To Do

You are going to build a circuit in order to answer the following question.

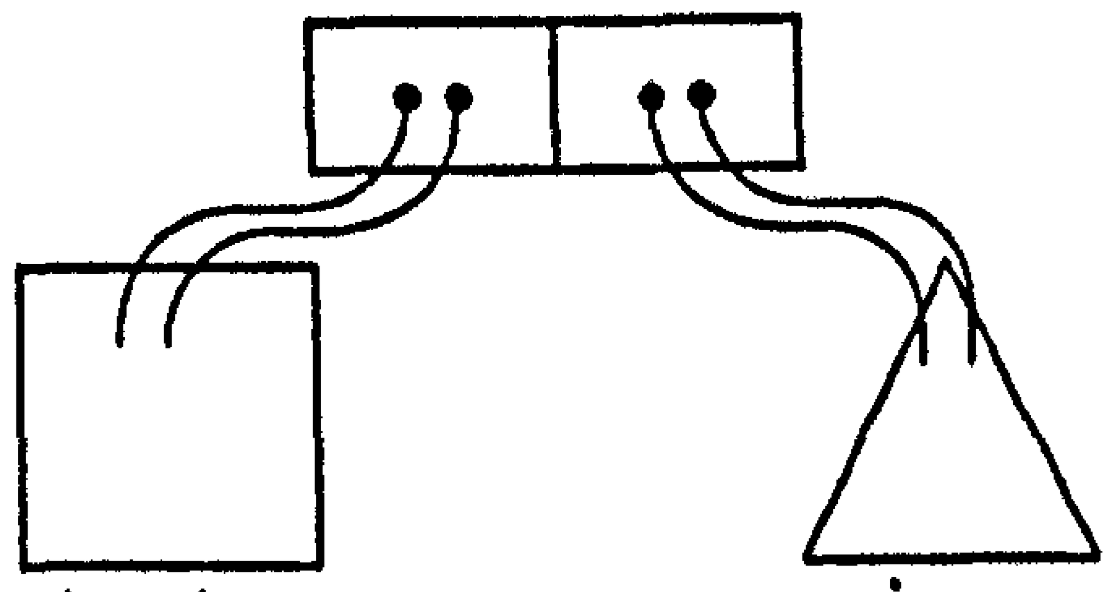
The two appliances are wired to the mains parallel with each other so that they may have the same

a) Current in them

b) Operating temperature

c) Voltage across them

d) Power supplied to them



a) Start up with

DISK labeled ELAB in Drive 1
DISK labeled ELAB —QUESTION in Drive 2

b) Select

BUILD

Now name the circuit

Q1

B To Answer the Question

a) You will need to create an AC circuit.

Select

CREATE (symbol for) AC SOURCE

and place it somewhere on the screen using the screen cursor keys.

What characteristics does an AC SOURCE have? When you create an object it is provided with certain properties. If you wish to look at these and/or change them in any way then you will need to select
SET ac1
Note that if you don't want to change anything you must press the key labelled
ESC

b) Model the Toaster and the Iron as resistors.

To do this, select

CREATE (symbol for) RESISTOR

position it on the screen

Think of this as the Toaster

Now repeat for the "Iron"

You might wish to change the default value of either the Toaster or the Iron. It is your decision.

c) Create the circuit by selecting

WIRE

and join up the power supply to the toaster. Now select

WIRE

a number of times in order to finish joining up the objects on the screen.

d) Select

RUN

and fill in as much of the following as possible:

Resistance of Toaster	=
Resistance of Iron	=
Current through Toaster	=
Current through Iron	=
P.D. across Toaster	=
P.D. across Iron	=
Power used by Toaster	=
Power used by Iron	=

e) Now choose

DISPLAY PD

and

RUN

to help you fill in more of the above

f) Now

DISPLAY POWER

and

RUN

g) Finally, fill in the resistances by selecting

SET res1

pressing

ESC

and repeating for "res2" —the iron.

This only applies if you have not already found out these resistances and (possibly) changed them.

h) Which option(s) of the original question is/are correct? _____

i) Repeat the above with a different value of the resistance of the Toaster. Select

SET res1

Remember that the Toaster was identified with the first resistor created.

and fill in the following:

Resistance of Toaster	=
Resistance of Iron	=
Current through Toaster	=
Current through Iron	=
P.D. across Toaster	=
P.D. across Iron	=
Power used by Toaster	=
Power used by Iron	=

j) Comment on the operating temperatures of the toaster and the iron:

----

k) Which option(s) of the original question is/are correct? _____

ELAB QUESTION:TWO

A What You Are Going To Do

You are going to build a circuit in order to answer the following question:

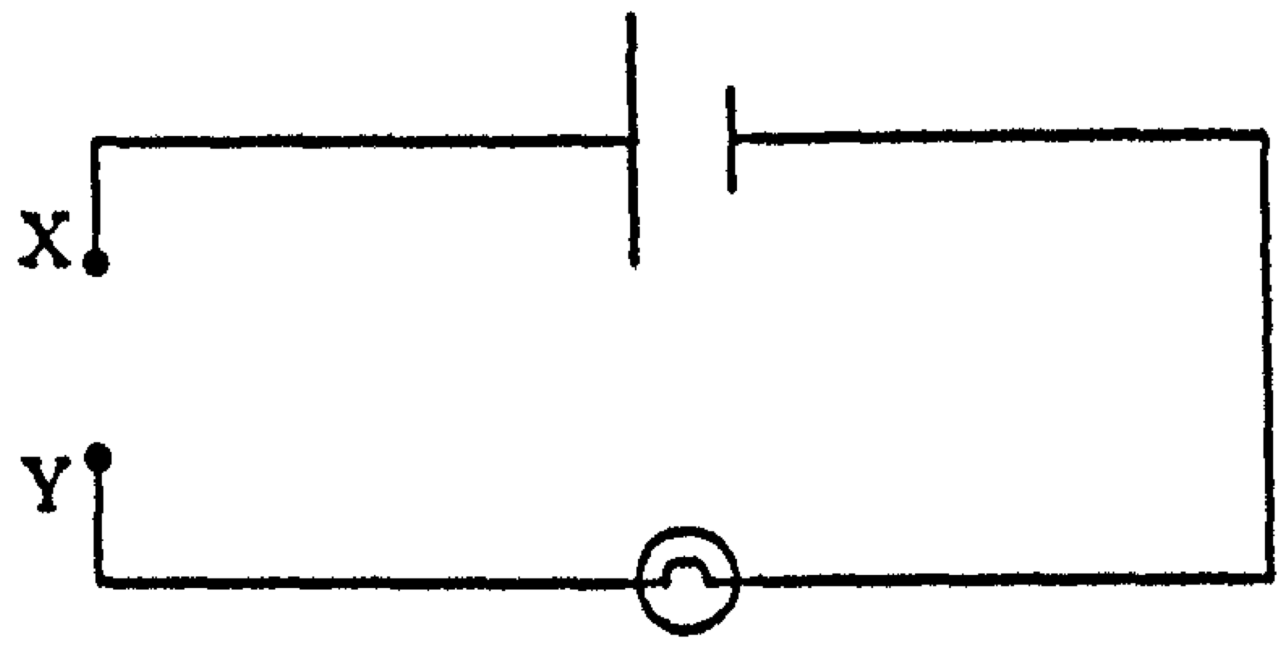
A student wishes to bridge the gap between X and Y so that the bulb may glow as brightly as possible. He should use a

a) Short thick conductor

b) Short thin conductor

c) Long thick conductor

d) Long thin conductor



a) Start up with

DISK labeled ELAB in Drive 1
DISK labeled ELAB —QUESTION in Drive 2

b) Select

BUILD Q2

B To Answer the Question

a) Model the circuit. First, create a power source by selecting

CREATE (symbol for) BATTERY

Now to create the piece of wire which, unlike the wires used to join up objects, is to have a resistance>0.

b) Select

CREATE (symbol for) RESISTANCE WIRE

The symbol is the fourth one from the top.

c) Now create a bulb by selecting

CREATE (symbol for) BULB

and position on the screen.

The symbol for bulb is the bottom one.

d) Join up the objects by selecting

WIRE

a number of times.

You will have to decide
- the length of a piece of short wire
- the length of a piece of long wire
- the diameter of a piece of thin wire
- the diameter of a piece of thick wire

e) Start with the short thick conductor by selecting

SET wir1

Now change its length by selecting

LENGTH

and enter its length in centimetres

Reselect

SET wir1

and this time change its diameter by selecting

DIAMETER

and enter its diameter in centimetres.

You will need to decide which measurement of:
CURRENT PD POWER V/I
determines the brightness of the bulb.

f) Now select

DISPLAY

and choose the output that determines the brightness of the bulb.

and

RUN

g) Repeat the above for the other three possibilities and fill in the following:

Length of long piece of wire =
Length of short piece of wire =
Diameter of thick piece of wire =
Diameter of thin piece of wire =

also, fill in

	Bulb Measurement Taken
Short thick conductor	
Short thin conductor	
Long thick conductor	
Long thin conductor	

h) Which option of the original question is correct? _____

ELAB QUESTION:THREE

A What You Are Going To Do

You are going to build a circuit in order to answer the following question.

A battery is connected to two resistors R and r in series. An additional resistance R′ is connected, in parallel with R, between N and M. Consequently:

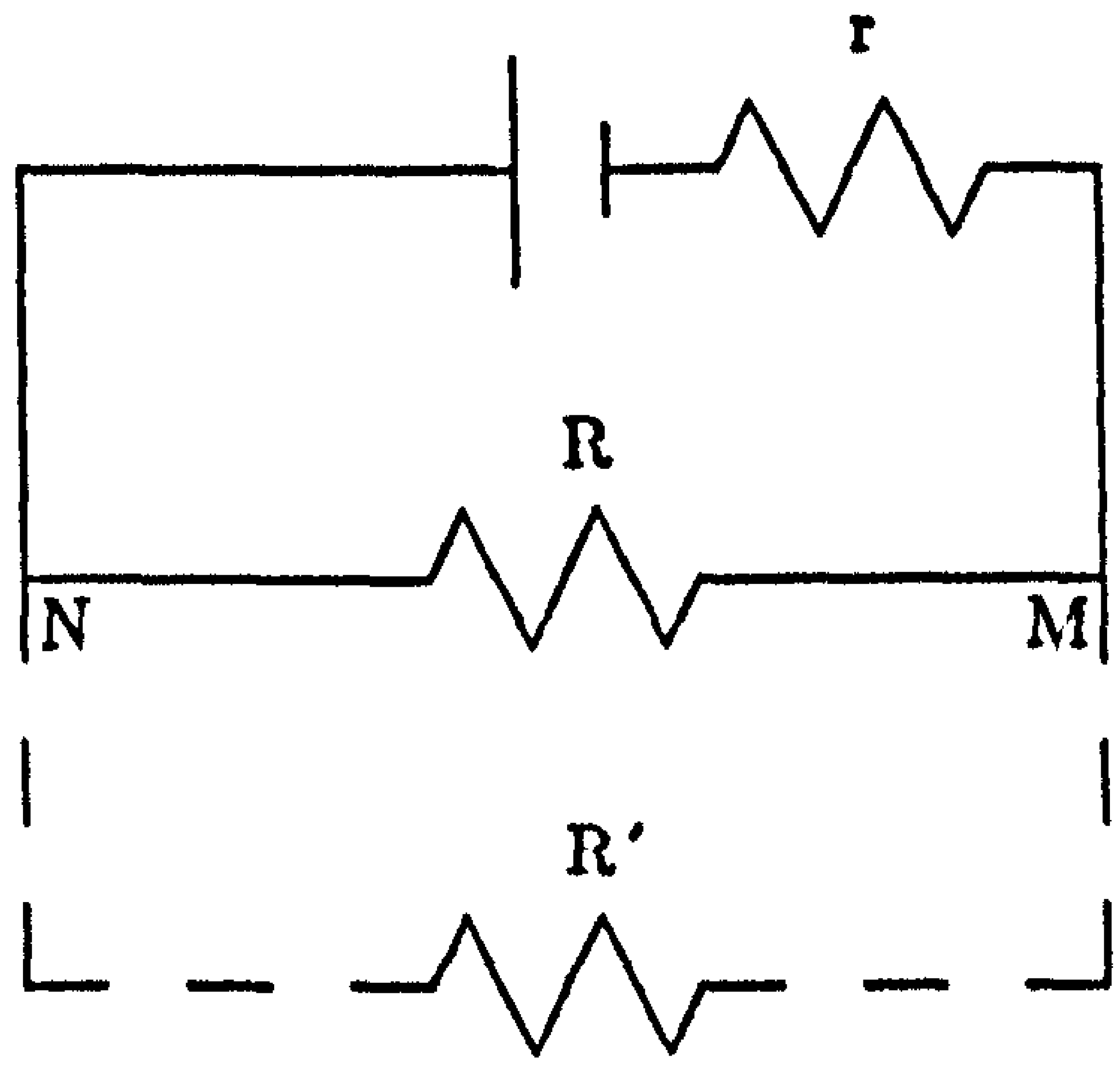
a) The current through r does not change, and the currents in R and R′ are inversely proportional to their resistances.

b) The p.d. between M and N does not change.

c) The current through r increases and the p.d. between M and N decreases.

d) The heat developed in R does not change.

e) The current through r increases and the p.d. between M and N increases.



a) Start up with

DISK labeled ELAB in Drive 1
DISK labeled ELAB —QUESTION in Drive 2

b) Select

BUILD Q3

B To Answer the Question

a) Model the initial circuit. First, create a battery by selecting

CREATE (symbol for) BATTERY

and position on the screen.

b) Now create the resistor R by selecting

CREATE (symbol for) RESISTOR

and position on the screen.

Note that R has been given a name "res1" by the program.

c) Create the resistor r by selecting

CREATE (symbol for) RESISTOR

and position on the screen.

> Note that r has been given a name "res2" by the program.
> You will need to assign values to the following:
> E.M.F. of Battery =
> resistance of r =
> resistance of R =
> using SET

d) Now wire up by selecting

WIRE

a number of times.

> You may find that you need to
> TURN
> an object if it is positioned badly.

e) Select

RUN

and fill in the first entry of the following:

current through r =
P.D. across MN =
Heat developed in R =

> To fill in the other entries you will need to alter the display of the current first to a display of the Potential Difference.

f) Select

DISPLAY PD

and then

RUN

and fill in the second entry above.

> To fill in the third entry, you must see a connection between the heat developed and the power converted from an electrical form to (mostly) heat.

g) Select

DISPLAY POWER

then

RUN

and fill in the final entry above.

h) Modify the circuit by adding the resistor R' in parallel with R by selecting

CREATE (symbol for) RESISTOR

position on the screen

Note that R' has been given the name "res3" by the program.

and then select

WIRE

twice to join up resistor R' (res3) in parallel with R (res2).

Now you will need to assign a value to:
resistance of R' =

i) Select

SET res3

and elect to change

RESISTANCE

Try setting the resistance of R' to twice that of R.

and then fill in the above entry.
j) Now select

RUN

and fill in as much of the following as possible:

current through r	=
P.D. across MN	=
current through R	=
current through R'	=
heat developed in R	=
current through R/current through R'	=
resistance of R/resistance of R'	=

k) Repeat the above but with different quantities displayed in order to complete the table.

This means selecting a different DISPLAY and then RUNning.

l) Comment on the correctness of each of the five possible answers to the original question:

a) ____

____

b) ____

____

c) ____

____

d) ____

____

e) ____

____

Appendix K

Exam Performance of Students using ELAB

The 'prelim' exam results for the S4 students:

Student	Percentage	Equivalent Grade
Student A	64	B
Student B	60	C
Student C	73	B
Student D	51	C

The 'O' grade exam results:

Student	Number Grade	Letter Grade
Student A	4	A
Student B	1	A
Student C	2	A
Student D	1	A

The 'H' grade exam results:

Student	Number Grade	Letter Grade
Student A	8	C
Student B	8	C
Student C	5	A
Student D	-	-

The 'O' grade exam results for the S5 students:

Student	Number Grade	Letter Grade
Student E	4	A
Student F	4	A
Student G	7	B
Student H	5	A

The 'H' grade exam results for the S5 students:

Student	Number Grade	Letter Grade
Student E	7	B
Student F	7	B
Student G	13	Fail
Student H	8	C

Note that Number Grades from one to five map to Grade A, Number Grades 6 and 7 map to Grade B and Number Grades 8 and 9 to Grade C.

Appendix L

Questionnaire for Students Using ELAB

Please fill in each of the questions below.

Ask for help if you need it.

1. Full Name
2. Date of Birth   3. Present Form
4. Name of Physics Teacher: This year
5. Name of Physics Teacher: Last year
6. a) Have you taken any Computer Science Course?

   b) If so, please describe in your own words:

7. a) Do you have access to a computer at home?

   b) If so, please describe in your own words:

8. Please respond to each of the parts with a number from 0 to 9 inclusive. 0 is to indicate no preference and 9 is to indicate a strong preference.

   If you have access to a computer what would you prefer to?

   a) Write Programs

   b) Play Games

c) Run Useful Programs

d) Run Educational Programs

9. Please respond with a number from 0 to 9 inclusive.
   0 is to indicate no hostility and 9 is to indicate great hostility.

   Do you see computers as hostile or friendly?

10. Hobbies —past and present. For what period of your life did you

    a) construct model aeroplanes, cars etc.?
    b) use LEGO or MECANNO?
    c) make cakes, cooked etc.?
    d) weave rugs, knitted scarves etc.?
    e) take apart/put back together bikes, clocks etc.?
    f) paint, sculpt, draw etc.?

11. Please respond with a number from 0 to 9 inclusive.
    0 is to indicate extremely bad and 9 is to indicate
    very good.

    a) How good do you think yourself at Physics?
    b) How good do you think your teacher thinks you are?
    c) How good do you think yourself at Electrical Circuits?
    d) How good do you think your teacher thinks you are?
    e) How good do you think you are at physics practicals?
    f) How good do you think your teacher thinks you are?

Appendix M

Performance Statistics for Students Using ELAB

In each of the following, the fairly simple-minded analysis is based on Spearman's Rank Correlation method.

M.1 Is Improvement Related to Question Complexity?

Comparison	Spearman's Rank Correlation Coefficient
Improvement vs Number of Facts	0.86
Improvement vs Number of Inferences	0.12
Improvement vs Facts+Inferences	0.92

M.2 Is Performance Related to 'O' Grade Results?

Comparison	Spearman's Rank Correlation Coefficient
'O' Grade vs Misconception Test	0.47
'O' Grade vs Construction Phase	0.10
'O' Grade vs Improvement	0.33

M.3 Is Performance Related to 'H' Grade Results?

Comparison	Spearman's Rank Correlation Coefficient
'H' Grade vs Misconception Test	0.82
'H' Grade vs Construction Phase	0.85
'H' Grade vs Improvement	0.85